4

Marine Physical Laboratorv

Report of a Workshop on the Geoelectric and Geomagnetic Environment of Continental Margins

A. D. Chave (Chair), AT&T Bell Laboratories
J. R. Booker, University of Washington
C. S. Cox, Scripps Institution of Oceanography
P. L. Gruber, AT&T Bell Laboratories
L. W. Hart, Johns Hopkins University
H. F. Morrison,
J. G. Heacock, Office of Naval Research
D. Johnson, Office of Naval Resarch

SIO Reference 90-20
April 1990

Approved for public release; distribution unlimited.

University of California, San Diego
Scripps Institution of Oceanography

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE:

3. DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S): SIO REFERENCE 90-20 [MPL-U-24/90]

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: University of California, San Diego

6b. OFFICE SYMBOL (If applicable): MPL

7a. NAME OF MONITORING ORGANIZATION: Office of Naval Research, Department of the Navy

6c. ADDRESS (City, State, and ZIP Code):
Marine Physical Laboratory
Scripps Institution of Oceanography
San Diego, California 92152

7b. ADDRESS (City, State, and ZIP Code):
800 North Quincy Street
Arlington, VA 22217-5000

8a. NAME OF FUNDING / SPONSORING ORGANIZATION: Office of Naval Research

8b. OFFICE SYMBOL (If applicable): ONR

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: N00014-89-J-3064

8c. ADDRESS (City, State, and ZIP Code):
800 North Quincy Street
Arlington, VA 22217-5000

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification): REPORT OF THE WORKSHOP ON THE GEOELECTRIC AND GEOMAGNETIC ENVIRONMENT OF CONTINENTAL MARGINS

12. PERSONAL AUTHOR(S): A. D. Chave (chair), J. R. Booker, C. S. Cox, P. L. Gruber, L. W. Hart, H. F. Morrison, J. G. Heacock, D. Johnson

13a. TYPE OF REPORT: summary

13b. TIME COVERED: FROM ______ TO ______

14. DATE OF REPORT (Year, Month, Day): 1990

15. PAGE COUNT: 37 pgs

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number):

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report constitutes the proceedings of the workshop on the Geoelectric and Geomagnetic Environment of Continental Margins held at AT&T Bell Laboratories in Arlington, Virginia in November 1989.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL: Spahr C. Webb

22b. TELEPHONE (Include Area Code): (619) 534-1844

22c. OFFICE SYMBOL: MPL

DD Form 1473, JUN 86 — *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

Report of a Workshop on the Geoelectric and Geomagnetic Environment of Continental Margins

Steering Committee

A.D. Chave (chair), J.R. Booker, C.S. Cox,
P.L Gruber, L.W. Hart, H.F. Morrison,
J.G. Heacock (ONR), D. Johnson (ONR)

Prepared for the Office of Naval Research under
Contract N00014-89-J-3064

April 1990

Table of Contents

Executive Summary

Antisubmarine warfare (ASW) surveillance has posed some major scientific and technological challenges to the Navy over the past thirty years which have largely been met using acoustic methods. Naval interest has recently been focussed on shallow water surveillance issues with emphasis on the continental shelf environment. Since acoustics has proven unreliable in shallow water due to a high ambient noise level and interactions with the bottom or surface, nonacoustic ASW surveillance methods have received increasing attention. Perhaps the most promising nonacoustic technique is based on detection of the electric and/or magnetic signature of a submerged target. Improving the performance of electromagnetic (EM) surveillance systems requires a better understanding of natural noise sources; the EM environment on the continental shelves is poorly characterized at present. A program of basic research aimed at developing a model and a deeper theoretical understanding of the sources of EM noise and delineating the electrical conductivity structure beneath and around the continental shelves would lead to significant improvements in the Navy's shallow water ASW surveillance capability.

The electrical structure of the continental shelves and the general shallow water EM environment is also of considerable interest to scientists in a variety of fields. There are two main sources of EM fields in the oceans, induction by external electric current systems in the ionosphere and magnetosphere and direct dynamo action of ocean water currents with the earth's main magnetic field. The fields produced by these sources are modified by interactions with conductive regions in and beneath the oceans and on the nearby continent. Despite our lack of knowledge about continental shelf electrical structure, this is an important region which provides the main electrical connection between the oceans and continents, a subject that relates to the nature of EM fields in the deep ocean, the composition of the earth's crust, and the rifting processes that create many margins, among other topics. The deep seismic structure under the continental shelves is not well understood and its electrical structure has never been studied, yet the complementary information provided by these two techniques is known to be more powerful than either taken alone. Better characterization of the spatial coherence properties of the externally-induced component of EM noise would lead to improved understanding of the complex magnetohydrodynamic processes producing them and has implications for electromagnetic studies of the earth's conductivity structure as well. In a similar vein, motionally-produced EM fields have never been measured on the continental shelves, yet studies of them would lead to a more complete understanding of shallow water hydrodynamics. It is clear that basic research in shallow water electromagnetics is important to a number of fields in the environmental sciences, and could be justified on scientific grounds alone.

In part because of these concerns, the Ocean Sciences (Code 112) and Applied Research and Technology (Code 12) directorates of ONR jointly sponsored a Workshop on the Geoelectric and Geomagnetic Environment of Continental Margins held at AT&T Bell Laboratories in Arlington, VA in November 1989. The purpose of this meeting, which involved about forty scientists from both universities and Navy laboratories, was both to define the basic research issues and to make recommendations for a focussed research program to help resolve them. A two day meeting format was selected, with the first day devoted to presentations by invited speakers that acted as a catalyst for subsequent extended discussions and the second day organized around four small working groups charged with identifying and prioritizing the major research issues and designing a few specific experiments to investigate these problems.

The principal recommendations of the meeting participants are:

- *The Office of Naval Research (ONR) should initiate a measurement-based multidisciplinary research program to understand the EM environment of the oceans, with emphasis on the continental shelves. The major components of such an effort include:*
    1. *Studies of the externally-induced EM fields at the earth's surface with the intent of improving our understanding of their temporal and spatial variability, leading to insight into the nature of the sources.*
    2. *Studies of the motionally-induced EM fields and their hydrodynamic sources with the intent of improving our understanding of their scales and origin.*
    3. *Experiments to better determine the electrical structure of the ocean-continent transition on both small and large spatial scales at active and passive margins.*
    4. *Studies of the interaction of natural EM fields with such structures.*
- *ONR should appoint a scientific advisory group on electromagnetic phenomena to represent the many disciplines that must be included in such a research program.*
- *ONR should fund a yearly workshop to foster cross-disciplinary fertilization between these areas and facilitate rapid dissemination of basic research results to scientists and engineers engaged in applying EM techniques to naval problems.*

This report constitutes the proceedings of the workshop. The remainder of this report is organized into four sections and seven appendices. Section I introduces the subject and motivates the need for basic research on shallow water electromagnetics, elaborating on some of the points made here. Section II develops the physical problem of interest to the Navy, describing some generic applications of EM to ASW. Section III contains an overview of the meeting discussions on the continental shelf EM environment, including aspects of ionospheric and motional noise characteristics and their interaction with the seafloor, with consideration given to Navy relevance issues. Section IV makes some specific recommendations for a focussed research program in this area. Appendices to the report contain a list of the steering committee membership and meeting attendees, a first day agenda, and the four second day working group reports. Readers familiar with Navy needs and desiring more detailed information on the scientific issues should scan Section I and read Section III. Readers who want a better justification of the proposed basic research in the context of Navy needs are directed to Section II. Readers interested in a more detailed summary of the meeting recommendations should examine Section IV. Further information on the scientific issues may be found in the last four appendices to the report.

I. Introduction

Antisubmarine warfare (ASW) surveillance has posed prominent scientific and technological challenges to the Navy since the end of World War II. Recent changes in the ASW threat have introduced new complications which are being met by efforts to develop advanced acoustic and nonacoustic sensing techniques supported by a variety of Navy organizations and commands. This report discusses basic research needs in electromagnetic (EM) geophysics relevant to one ~~such~~ endeavour ~~which have been~~ identified as important science issues and ~~which can have~~ a significant impact on Navy nonacoustic ASW surveillance programs.

Over the past thirty years, a major ASW emphasis has been placed on long range, deep ocean surveillance using passive acoustics and the subsequent tactical localization of submerged targets using passive and active acoustics or airborne magnetic anomaly detection (MAD). Because of recent and dramatic improvements in the acoustic quieting of foreign submarines, traditional forms of surveillance have lost some effectiveness. As a result, there is an increasing focus on long range, low frequency active acoustics in the deep ocean as a supplement to passive techniques, as well as more emphasis on acoustic barrier techniques. Reduced acoustic surveillance efficiency has also led to renewed interest in nonacoustic ASW methods, including those based on measurement of electric and magnetic fields. Several Navy applied development programs are currently ~~under way to improve~~ EM surveillance methods without a fundamental understanding of the noise background against which EM systems must operate.

While EM field detection has potential uses in both the deep ocean and shallow water, this report emphasizes the latter. There are both immediate operational needs and important geophysical issues that dictate this emphasis. For example, acoustic techniques are limited by bottom or surface reverberation and a high ambient noise level in shallow water, yet there is increasing concern about submarine operations in such areas, especially in the Arctic where shallow water is common. For reasons of proximity and logistics, this report will further focus on basic research problems on North American continental shelves. Many of the relevant physical phenomena that control EM field behavior on the shelves will also be present in more distant shallow seas, so the basic research suggested in this report is of wide naval relevance. Since our ignorance about the EM environment is greatest in shallow water, the prospect for significant improvement in surveillance capabilities is correspondingly large.

The continental shelves are composed largely of submerged continental lithosphere and are located at the margins of large land masses. They retain the complex geologic history and structures of the continents, and their location at the discontinuity between ocean and land as well as the relative shallowness of the water layer leads to energetic and often nonlinear oceanographic processes. Natural electromagnetic fields in the ocean are generated both by external (ionospheric and magnetospheric) current systems and by the dynamo interaction of conductive seawater moving through the earth's magnetic field. Since the EM environment is a direct function of these sources as modified by induction in surrounding electrical structures, principally the sediments, crust, and mantle beneath the earth's surface, a thorough understanding requires a multidisciplinary approach. This is especially true on the continental shelves.

There are many questions about the sources and behavior of background EM fields on the continental shelves that are of strong interest to the basic geophysics community. Both the temporal behavior and spatial coherence lengths of ionospheric and hydrodynamic noise sources remain poorly characterized, yet are key unmeasured parameters required to understand the sources themselves, and have implications for noise level estimates that are important in both research and naval applications. The continental shelf provides the main electrical connection between the oceans and continents, a subject which concerns the composition of the earth's crust and structural features beneath continental margins. The latter is a fundamental topic in geophysics that relates to continental rifting and convergence mechanisms, and was the subject of a recent National Research Council study which recommended a research initiative in this area [Ocean Studies Board, *Margins: A Research Initiative for Interdisciplinary Studies of Processes Attending Lithospheric Extension and Convergence*, National Academy of Sciences Press, 1990]. The deep seismic structure beneath the continental margins is only poorly characterized, and its electrical structure has never been studied, yet the information obtained from seismic and EM geophysics is complementary and known to be more powerful taken jointly than individually. This is only a brief list of basic research problems that will be expanded on later in this document. It should be recognized at the outset that this report specifically emphasizes fundamental understanding of the relevant physical and geological processes causing and influencing EM fields in the continental shelf environment. Applied research issues such as sensor development, technological improvements, and signal processing needs are not specifically addressed. This is not because of a perceived lack of importance, but rather due to a strong belief that they should be driven both by Navy needs and by the products of basic research.

The Ocean Sciences (Code 112) and Applied Research and Technology (Code 12) directorates of ONR decided to jointly sponsor a Workshop on the Geoelectric/Geomagnetic Environment of Continental Margins both to define the basic research issues and to make recommendations for a research program to help resolve them. The meeting was organized by a steering committee (Appendix A) and held in November 1989 at AT&T Bell Laboratories in Arlington, Virginia. About forty scientists from universities, Navy research facilities, and Navy commands attended the workshop (Appendix B). Because the workshop was to involve strong participation by the academic community, the meeting content was restricted to unclassified material. A two day meeting format was selected, with the first day devoted to presentations by invited speakers and subsequent extended discussions (Appendix C). On the second day, four working groups were formed and charged with identifying and prioritizing the major research issues with some emphasis on Navy needs, designing a few specific experiments to investigate these problems, and providing a written summary. This report contains a synopsis of the meeting discussions and recommendations.

II. Technical Issues in EM Surveillance

The primary naval applications of EM for shallow water ASW occur in 1) fixed systems and 2) airborne systems. In both cases, the performance of a prototype surveillance system depends on the ability to extract target signatures from noise. Basic research issues such as the characterization and interpretation of spatial and temporal scales of EM noise sources and the influence of local sub-bottom electrical structure on the EM signal level are important in the design of both surveillance hardware and detection processing algorithms. In particular, it is essential that the influence of natural noise be reduced as much as possible to make full use of existing or future sensors of increased sensitivity.

A submarine may have static magnetic and electric dipole moments caused by residual magnetization of the machinery and hull and by corrosion-induced electric currents flowing from the hull through the surrounding water. In addition, moving machinery or electronic devices may generate frequency-dependent EM fields. For an observer in or above the ocean, these fields can be described using a standard multipole expansion given the source magnetic or electric dipole moments and auxiliary information about the electrical conductivity of the local environment; to lowest order and in the far field, the dipole term will predominate. If the submarine is moving, then its static dipole moment will appear to produce a transient EM field as it progresses past a fixed sensor emplaced on the seafloor. Such a transient can be converted to its frequency-domain equivalent, and the peak apparent frequency is approximately the target velocity divided by the slant range. In water of 300 m (i.e., shelf/slope) depth and for velocities covering a range of 1-10 knots (0.5-5 m/s), the relevant frequencies vary from about 10^{-3} to 10^{-2} Hz. Higher frequencies might become of interest if shorter ranges and/or larger velocities are important, and lower frequencies are emphasized at longer ranges. Higher frequencies might also be important for other types of sources. Finally, since the EM field is a vector quantity, measurement of the individual components can in principle yield information about the heading of a submarine if the reasonable assumption that the source dipole is oriented along the long axis of the hull is made. Information on its velocity is also available by considering the frequency dependence of the EM signature, or equivalently, the shape of the transient. Figure 1 shows a model calculation for the electric field due to a moving subsurface dipole observed by a fixed sensor at the seafloor in the time domain. Figure 2 is the frequency domain equivalent. One obvious ASW application of EM detectors is the construction of a barrier system for surveillance in which one or more lines of sensors are emplaced on the seabed to detect submerged intruders.

There are a number of basic research issues that impinge on the operation of a fixed barrier system. These will be discussed in more detail in the next section. Clearly, it will be necessary to remove as much of the natural EM noise as possible from the data stream to isolate potential targets and maximize the performance of sensors and detection algorithms. It is highly desirable that this be accomplished in near real time. For a fixed sensor, the noise due to ionospheric variations will be dominant at frequencies below 0.1 Hz. In addition, oceanic noise is important and remains poorly characterized at present. Because of the large conductivity contrast between land and ocean as well as sub-seafloor structural features, concentration of natural electric currents can result in substantial modification of the EM fields in coastal areas. None of these topics is very well understood, yet knowledge of their magnitude, spectral behavior, and correlation scales has strong implications for the design of a barrier system and corresponding estimates of the noise reduction that can be achieved. While the empirical approach of simply subtracting the signals at adjacent sensors to remove the noise may be considered, it has several serious drawbacks. First, it can only be effective if the relative gains of the different sensors are known with sufficient precision. Second, while subtraction may remove ionospheric noise because its correlation scale is usually large compared to a practical sensor spacing, subtraction cannot reduce oceanic noise whose coherence lengths are of the order of or smaller than the sensor spacing. Motional sources with small scales in the frequency band of interest are ubiquitous. It is clear that more sophisticated noise reduction schemes are needed, and that these can be designed only if a better understanding of the basic geophysical problem is attained. It is likely that the payoff from a basic research effort for naval applications would be substantial on the short term.

While it has received recent attention, fixed barrier systems are not the only ASW application of EM. Towed total field magnetometers have been in use for many years by the Navy, especially in an airborne mode on patrol aircraft for MAD. Due to its short effective range, MAD has historically been used principally for target localization and to control weapons drop, although it may also be useful for trailing submarines after they are detected acoustically. The approaches used

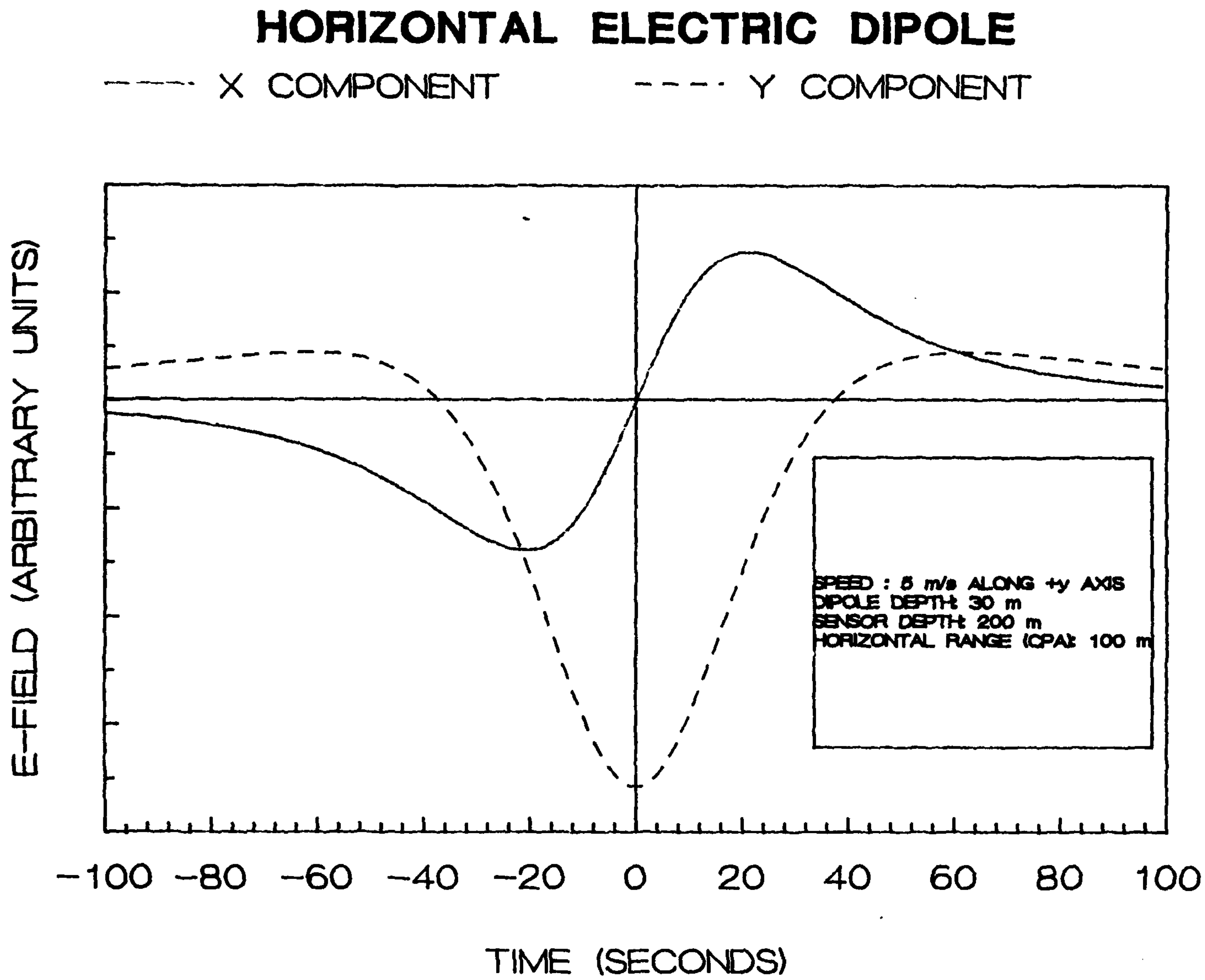

Figure 1. The time domain voltage observed by a fixed sensor on the seafloor at 200 m as a static electric dipole source moves past it. The units of the electric field are arbitrary. The target is 30 m deep, has a velocity of 5 m/s along the y-axis, and will pass at a horizontal range of 100 m at closest approach. The solid line shows the electric field at a right angle to the dipole track (and hence orthogonal to the direction of the dipole moment), while the dashed line shows the electric field in the y direction (courtesy of P.J. Evans, AT&T Bell Labs).

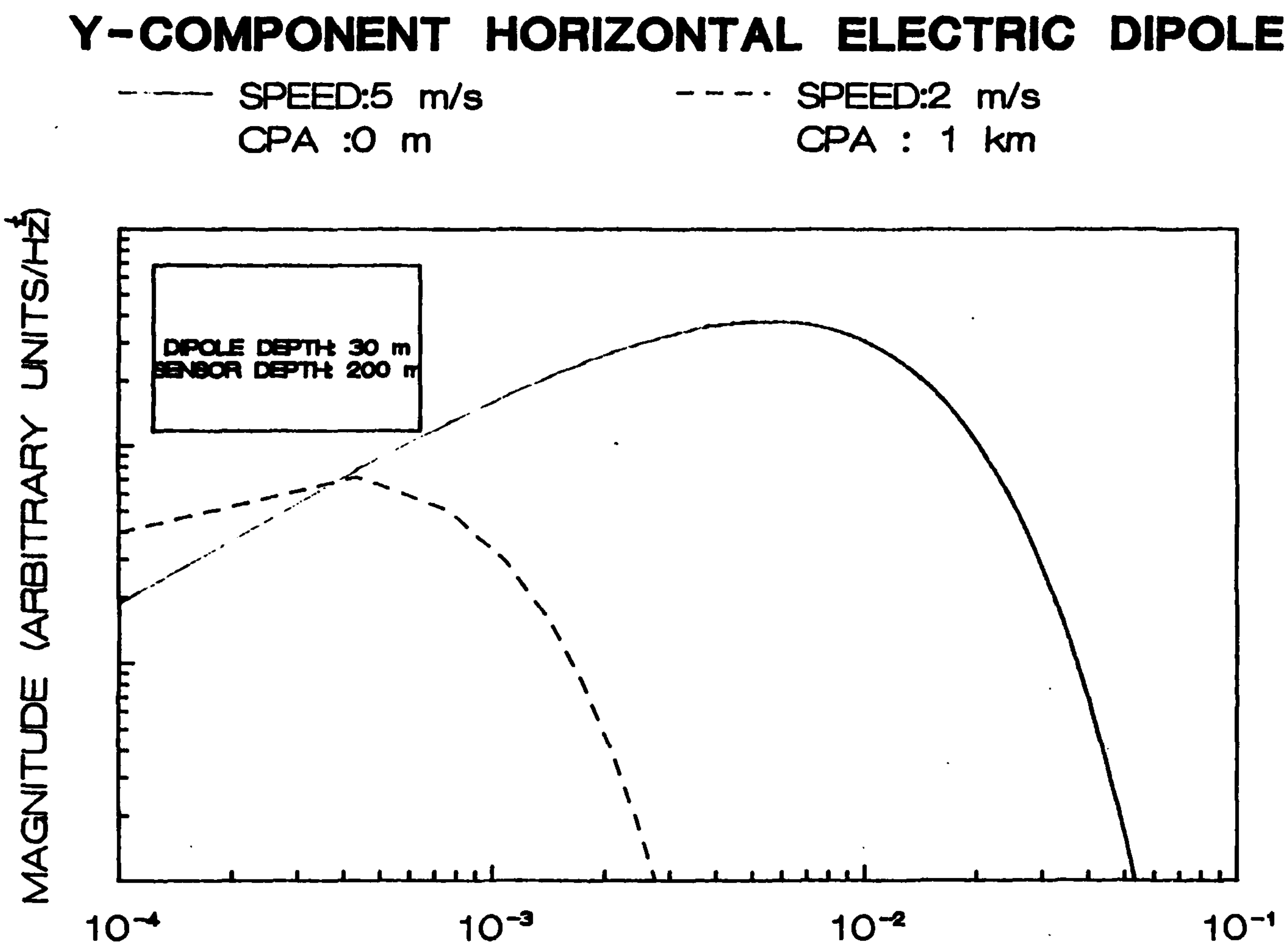

Figure 2. The frequency domain form of dipole transients similar to those shown in Figure 1. The dipole source of arbitrary moment is at a depth of 30 m, while the sensor is on the bottom at a depth of 200 m. The electric field is in the direction of the dipole source. The solid line shows the Fourier transform magnitude for a dipole moving at a velocity of 5 m/s passing directly over the sensor (no horizontal range at closest approach). The dashed line shows the Fourier transform magnitude for a slower dipole (2 m/s) off to the side, with a horizontal range of 1 km at closest approach (courtesy of P.J. Evans, AT&T Bell Labs).

here are quite different from those for a fixed sensor system. No airborne equivalent of a fixed electric field sensor has been developed, so only magnetic field detection has received consideration. Because of platform motion considerations, measurement and interpretation of the vector magnetic field is quite difficult, and the total field receives the greatest attention. The detection issue becomes one of finding the static magnetic signature of a submarine amidst geological and oceanic magnetic field noise. As for a fixed sensor and a moving target, a static magnetic dipole appears as a transient event with a qualitative resemblance to Figures 1 and 2 for a sensor moving much more rapidly than the target. This has a peak frequency given approximately by the frequency of encounter or sensor velocity divided by the target slant range. For an aircraft moving at 50 m/s (100 knots) and a target range of 100-1000 m, this gives a frequency band of 0.05-0.5 Hz.

The technical and basic research issues for fixed and moving sensors are generally quite different, although there is certainly some overlap. This primarily reflects the diverse sources of noise for the two methods. For example, unlike for a fixed sensor, any background magnetic disturbance with an effective size ranging from a few meters to a few kilometers which is stationary or moving slowly with respect to a moving sensor may produce a signal in the airborne ASW frequency band. This certainly includes variations in the magnetization of the seafloor as well as induction processes in small scale conductivity anomalies, but oceanic sources can also produce problems. As an example of the latter, deep ocean internal waves produce very weak EM fields at intrinsic frequencies ranging approximately from a cycle per day to a cycle per hour, and are clearly of no consequence for a fixed ASW system. However, such internal waves have characteristic wavelengths ranging from meters to kilometers, and their magnetic influence on a moving sensor will be observed in the ASW band and therefore serves as a natural noise floor below which further sensor performance improvements would be futile. Determination of such noise characteristics is a basic research problem. Correction for the geologically-induced magnetic field noise requires a combination of improved mapping of the magnetic field and conductivity structure on increasingly fine scales and real-time navigation with a resolution of meters. While the first and last of these are largely applied problems, determination of the seafloor conductivity structure in the transition zone addresses cutting edge scientific questions. However, the mapping requirements are increasingly stringent as the sensor moves closer to the source, such as on the continental shelf, and may be impractical. In addition, a moving platform will produce sensor motion covering a range of frequencies. For a vector magnetic field detector, even very small rotations in the relatively strong geomagnetic field will produce very large noise signals; at mid-latitudes, 10^{-5} radian of rotation corresponds approximately to 0.01 nT. The rotation problem has led to increasing interest in the development of a magnetic gradiometer. There is a strong technological (applied research or development) rather than basic research thread to these problems. While better understanding of the ionospheric and oceanic sources of EM noise and boundary effects on its magnitude will benefit the airborne EM community, improvements for naval applications must be achieved in combination with technological developments which reduce the large influences of local geology and platform motion. Furthermore, a better understanding of the research topics relevant to fixed sensors can quickly be transferred to the airborne side, while the reverse will be more difficult. For these reasons, the workshop participants feel that a basic research effort emphasizing fixed sensors has the greatest potential for a short term applications payoff and the best chance of success. As will be discussed in the remainder of this report, such a study also represents a strong contribution to basic geophysics.

III. An Overview of the EM Basic Research Issues

The geophysical problem divides loosely into a consideration of the sources of EM fluctuations and an examination of their interactions with the earth. The two major natural sources of EM fields on the continental shelf are ionospheric or magnetospheric variations and motionally-induced fields caused by local water motions. The former are typically (but not always) of scales larger than 100 km or so, while the latter produce strong EM fields with scales of meters to kilometers. While they have very different gross characteristics and especially spatial scales, the EM fields produced by both of the natural sources interact strongly with the underlying seafloor. There are two closely related but distinct aspects of the interaction phenomenon that are considered separately in this report because they have different implications for the Navy. The first involves induction on a small scale (a few meters to a few kilometers) due to conductivity anomalies in the ocean and seafloor such as might be associated with topographic features or ocean fronts. The second induction phenomenon is much larger scale and associated with the conductivity transition between ocean and continent. This will produce electric current concentration and concomitant enhancement of the ionospheric and large-scale oceanic noise fields.

Ionospheric and Magnetospheric Sources

The ionospheric working group has concluded that the detailed morphology of the EM fields produced by external current systems in the frequency band $\approx 10^{-3}$ to $\approx 10^{3}$ Hz are comparatively unknown. Strong spatial effects from many of the ionospheric sources are expected based on the relevant physics, especially at high (e.g., Arctic) latitudes. It is essential to have good long term statistical information about field behavior before a more detailed understanding of short term temporal behavior can be achieved. Good statistical characterizations (e.g., power or two-point frequency coherence spectra) do not exist in large part because of the strong nonstationarity exhibited by the ionosphere. In particular, this means that estimates of the relevant correlation scales and their temporal variability are rarely available, and may cover limited regions or short time intervals for the few cases that exist.

The Navy needs to appreciate at the outset that much of past space physics research may not be appropriate for addressing the problem of predicting and removing ionospheric noise contamination. Most space physics research tends to be process oriented; the research task is aimed at understanding a specific part of the overall physics using a variety of data. In recent years, many of the necessary data have been acquired *in situ* with spacecraft rather than using ground-based instrumentation. Furthermore, most space physics research in the past couple of decades has involved the the study of distinct types of events that constitute only a fraction of the geomagnetic record rather than long term statistical averages or more general ionospheric behavior. Such quantities as coherence scales or nonstationarity have usually been of secondary interest. Thus, while existing space physics data are applicable to understanding Navy-relevant problems, the necessary questions are rarely being asked at present. As a corollary to these statements, one must consider the extent to which it is necessary to understand or characterize the ionospheric field variations to remove them from data. For example, it is common lore that since the ionosphere is of order 100 km or more away from the earth's surface, the EM fields that are seen on the ground will not contain components with scales significantly smaller than this. This is certainly true at some level; if it is desired to remove up to say 95% of the ionospheric component from a given set of data, then a contribution from short wavelength components is probably not important. Whether or not this remains true at the 99% or 99.9% level is not known. If real time noise cancellation at the 99% or higher level is desired, then the situation is problematical and certainly requires some research. For example, some atmospheric electricity sources are much closer to the earth's surface than 100 km, and can have very small scale effects; the occurrence of such sources around the globe is not well understood. At this time, we are not in a position to address practical issues about the extent of noise cancellation that can be achieved statistically, let alone on a real time basis.

This can be illustrated by considering a few of the processes discussed by the ionospheric working group. Hydromagnetic waves constitute a major source of ionospheric fluctuations in the $\approx 10^{-3}$ to 10^{-1} Hz band. While these have been extensively studied and are reasonably well understood in a gross theoretical sense, some important properties have not really been examined. Neither the coherence extent at short scales ($\approx$100 km) nor the latitude variability have been well characterized. There is good reason to believe that location-dependent effects are significant, especially at auroral and polar latitudes where shorter scales may become dominant. Another important low frequency source is ionospheric currents of many types. These tend to concentrate at auroral latitudes, so edge effects may be a significant source of short scale fields at these points. This has obvious implications for Arctic applications of EM. At higher frequencies, the dominant source of external fluctuations is from lightning and related phenomena. ELF and VLF signals from nearby lightning storms can be very localized and the signal from ground and intracloud discharges can be quite spatially non-uniform.

The power spectrum of natural EM fields is quite nonstationary, but generally exhibits a rapid fall-off ($\approx f^{-3}$ in the magnetic field) between 10^{-3} and 10^{-1} Hz with a minimum near 1 Hz. Power rises slowly above 1 Hz, but the EM fields become dominated by transient events. From a Navy needs viewpoint, the most important ionospheric effects will occur at the low frequency end of the 10^{-3} to 10^{3} Hz band. Given finite resources, it is this region in which the greatest effort should be concentrated.

Important information on ionospheric and magnetospheric physics would be acquired by addressing these problems, as further detailed in Appendix D. Study of coherence scales and general ionospheric processes is facilitated by using spatial arrays of magnetometers at the earth's surface. Much of this data already exists in archival form. Ground-based arrays provide data that cannot be obtained using spacecraft; it is difficult to envision emplacing sufficient satellites within the magnetosphere to simultaneously sample its properties at widely separated points. Spatial coherence scales, polarization properties, and propagation velocities for specific events can be determined from magnetometer arrays, and give important clues on physical processes in the source region. Thus, the sort of practical information desired by the Navy is also useful for basic research purposes in space physics.

Ocean-induced EM Fields

The state of uncertainty is even greater for motional EM fields than for ionospheric sources, largely because of the paucity of actual measurements. While there are a small number of electric field data sets from the deep ocean at depths of 1500 m or more covering the 10^{-3} to 1 Hz band, higher frequencies are difficult to measure because of instrument noise limitations. Figure 3 shows some typical deep water electric field power spectra. Electric and magnetic field data at frequencies below about 10^{-2} Hz have been collected at a number of sites in the deep ocean by

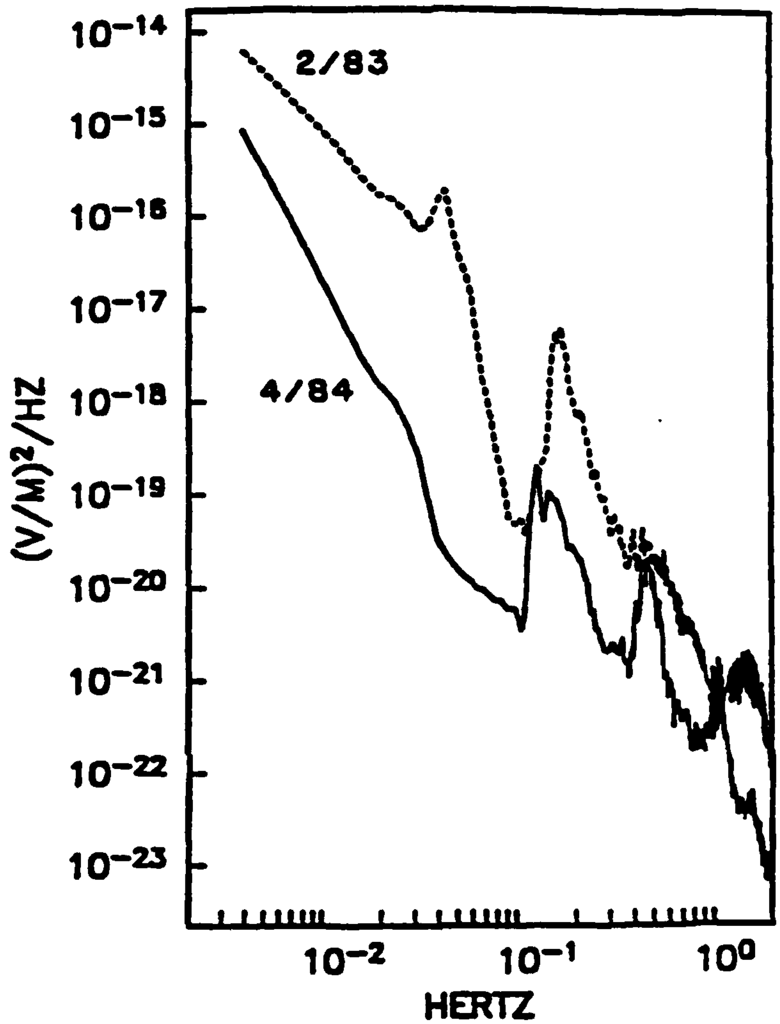

Figure 3. Power spectra of electric field time series collected off of San Diego in 1983 and 1984 in about 1000 and 2000 m of water respectively. At frequencies lower than about 0.05 Hz the spectrum is dominated by ionospheric noise and long gravity waves. The prominent peak immediately above 0.1 Hz is due to microseisms. The additional peaks at higher frequencies that are more prominent in the deep water data set are due to Rayleigh wave modes in the sedimentary layer (from Webb and Cox, *J. Geophys. Res., 91*, 7343–7358, 1986).

academic investigators for geophysical and oceanographic studies, but are not relevant to this report. No such measurements have been collected on the continental shelf or in water shallower than 1000 m. The bulk of what is known about the continental shelf EM environment is based on theory. While this is reviewed both here and in Appendix E, it must be recognized that a theoretical calculation can be no better than the estimates of the relevant physical parameters that enter it. In this instance, those estimates are often mere guesses.

A major source of EM fields on the continental shelf will be internal waves and turbulence. Deep ocean internal waves are reasonably well characterized, but internal wave behavior on the shelf is quite different, typically consisting of episodic packets rather than steady state fluctuations. Their effects are expected to be confined to the lower end of the 10^{-3} to 10^{3} Hz band. Shallow water internal wave packets are frequently highly nonlinear soliton-like disturbances generated near the shelf edge by tidal interactions with topography and propagating shoreward. Internal solitons have been studied in a few places, but are not well understood. Theoretical calculations suggest that their EM signature is large and that their character might be confused with submarines due to their very dipole-like form in the time and frequency domains. The spatial scale of solitons ranges from a few hundred meters to a few kilometers. It is likely that soliton occurrence can be predicted due to their association with the tides, although this requires further attention. Other types of internal waves may also exist on the shelf. These require much better characterization before their EM properties can be assessed.

The presence of bottom boundary layers on the shelves suggests that models of turbulence may be useful for estimating their EM effects. Order of magnitude calculations indicate that turbulence in the bottom boundary layer is a strong source of noise to seafloor electric field recorders, with characteristic scales ranging from a few to a hundred meters. Their magnetic effects are comparatively weak due to the smallness of the induction number.

Surface gravity waves are another major source of induced EM fields on the shelves. Theoretical computations of their EM effects have been presented by numerous authors, and there are in addition a few measurements. Swell and wind waves generate weak fields with spatial scales of a few tens of meters over the frequency range of 0.05 to 1 Hz. Their effect at the seafloor is limited when the water depth exceeds 100 m or so. However, long gravity waves appear to be a ubiquitous feature of the continental shelves and can produce EM fields comparable to those from the ionosphere at the low frequency end of the band. Due to their large wavelength (many kilometers), long wave EM fields will be correlated over significant distances. Long waves are quite nonstationary on time scales of days due to generation by local and nonlocal storms. In addition, special types of surface waves can exist close to the shoreline. Probably the most important type in the present context is edge waves or shore swash which may have significant wave heights and are trapped to the coast, decaying offshore. Edge waves have characteristics intermediate between those of long waves and swell.

Elastic (i.e., Rayleigh) waves are the primary source of induced EM fields on the deep seafloor at frequencies between 0.05 and 1 Hz. Their spatial scales are typically many kilometers at low frequencies to a few meters at the high end. It is very difficult to estimate the importance of these seismoacoustic waves in shallow water because their properties depend critically on the elastic characteristics of the seabed and the local size of the excitation. Such information is not readily available for the shelves. Further theoretical work is warranted, but must be validated by actual measurements.

A final type of motional field is due to advection of small scale conductivity anomalies in the water column by larger scale currents. For a fixed sensor, these might be an important low frequency source of noise if the size of the anomalies is small and the advection velocity is large in a manner analogous to geologic noise on an airborne magnetometer. A specific type of small scale conductivity anomaly that deserves attention is associated with thւ passage of ocean fronts. These are nearly linear features across which large temperature/salinity gradients and horizontal shear may occur, and have scales from about a hundred meters to a few kilometers. Strong EM gradients will be associated with fronts. Some special types of continental shelf fronts called squirts may be especially important in the present context.

Little is known about motional EM sources at high frequencies (>1 Hz). It is probable that turbulence is a major player here, but other types of sources need to be examined. The lack of knowledge largely reflects the absence of any EM measurements in this frequency range either in the deep ocean or on the shelves.

The sources of EM fields will be somewhat different at the two extremes of the continental shelf. Near the seaward edge of the continental shelf, the dominant sources are probably surface waves, turbulence, internal waves (including solitons), and maybe seismoacoustics. Ocean fronts may also be of some significance on the deeper parts of the shelf. Near the coast, the same processes are likely to be augmented by edge waves, and swell effects will become more important as the water gets shallower. Soliton fields are likely to be especially intense in shallow water when these nonlinear waves are present.

It must be noted that a strong thread of ignorance pervades this subject. The assertions made here are extrapolations of a few deep ocean measurements using theoretical calculations of dubious applicability. The major limitation is the lack of continental shelf measurements. Until such data exist, detailed theoretical calculations are not warranted, although simple, order of magnitude calculations are essential to guide experimental design.

It should also be emphasized that all of the oceanic phenomena mentioned here are of interest to oceanographers in their own right. Any study of the EM effects of these types of disturbances must be accompanied by auxiliary measurements sufficient to define the forcing function (i.e., the hydrodynamic or acoustic field), and such data are of considerable general use. For example, a better understanding of shelf internal waves and turbulence has implications for mixing processes which clearly impact on physical oceanography and biology. The importance of surface gravity waves and Rayleigh waves for low frequency acoustic noise models is also profound. In some cases, electric field measurements have proven to be among the best ways to study the hydrodynamics or physics; a prominent example occurs in low frequency acoustics (i.e., Rayleigh waves in the seafloor). Thus, a focussed research effort on continental shelf motional EM fields has implications for a variety of fields, and clearly transcends electromagnetics alone. In addition, an improved understanding of the motional EM noise sources on the continental shelf is of importance to academic investigations of the electrical conductivity beneath them. Both passive (e.g., magnetotelluric) and controlled source EM experiments to study the structure of the seafloor are influenced by noise, and this noise can be removed or corrected for only if its characteristics are better understood. Finally, the sort of data that must be collected to understand the motional EM fields can usually be applied to studies of the conductivity structure of the underlying seafloor as well. This may require slightly more sophisticated instruments and coordinated experimental planning, but the additional science that is achieved for a small increment in cost is considerable.

Interactions with the Seafloor

A thorough review of continental margin geology or oceanography is certainly beyond the scope of this document. In a geologic sense, most of the North American margins consist of passive types (e.g., the US east coast, Arctic) where present day tectonism is not evident, the shelf is comparatively wide (≈100 km or more), sediment accumulation to tens of km has occurred over long time spans (100 my or more), and erosional processes by rivers and changing sea level are important. However, the US west coast is more varied. From California to Oregon it is translational with a narrow (tens of km) shelf and minimal sediment accumulation in shallow water. North of the Oregon-California border and in southern Alaska, the margin is active, with present day subduction occurring at the continent edge and a deep trench serving as a trap for continental sediments. While little is known about the electrical structure beneath any of these margin types, it is geologically reasonable to expect substantial differences so that no one conductivity model will be universally applicable.

Two working groups considered interactions with the seafloor on small and large scales, although there is considerable overlap. Local induction fields may be modified by anomalous small scale (up to a few kilometers) conductive structures both by causing enhanced electric current flow, including channeling of current from distant places, and by serving as the locus for electric charge concentration. These processes are reasonably well understood when the inducing field is ionospheric and hence of large scale compared to the anomaly. This is not true when the source scale is small or variable, as is frequently the case for motional induction. However, a major and necessary piece of information is missing. We have only limited data on the scale and magnitude of electrical conductivity granularity on the deep seafloor, let alone on the continental shelves. The subbottom conductivity structure will be more variable on the shelves because of a complex geologic history. Thus, until some surveys of the electrical structure are obtained, it is difficult to estimate the importance of small scale conductivity anomalies to the interpretation of EM data. Small scale, shallow surveys of electrical conductivity are best accomplished using controlled sources. A few detailed conductivity surveys employing controlled source EM methods would be of considerable interest to the basic research community. Such research must be regarded as largely exploratory, in part because the techniques needed to acquire controlled source EM data are in a nascent state at present. This means that a very useful by-product of continental shelf research in this area would be further development of seafloor controlled source EM methods, and in particular more extensive understanding of how to use controlled source systems in a towed (from a surface ship) mode to cover a large area as rapidly as possible (Figure 4). If towed controlled source EM reaches a state of maturity such that it can become a useful general tool to the marine geophysicist, it could have a substantial impact on the field.

The larger scale electrical transition between ocean and continent is also of considerable interest to solid earth geophysicists. The continental shelves constitute the electrical connection between the deep ocean and the continents, and are poorly characterized. The very large conductivity contrast between seawater and land as well as major changes in subsurface structure associated with the transition between ocean and continent strongly concentrate large scale electric currents over the continental shelves. The principal effect is to enhance the regional electric and magnetic fields, an effect which can be diagnostic of subsurface structure. This also means that the ionospherically-generated noise level in the electric field may be substantially higher than

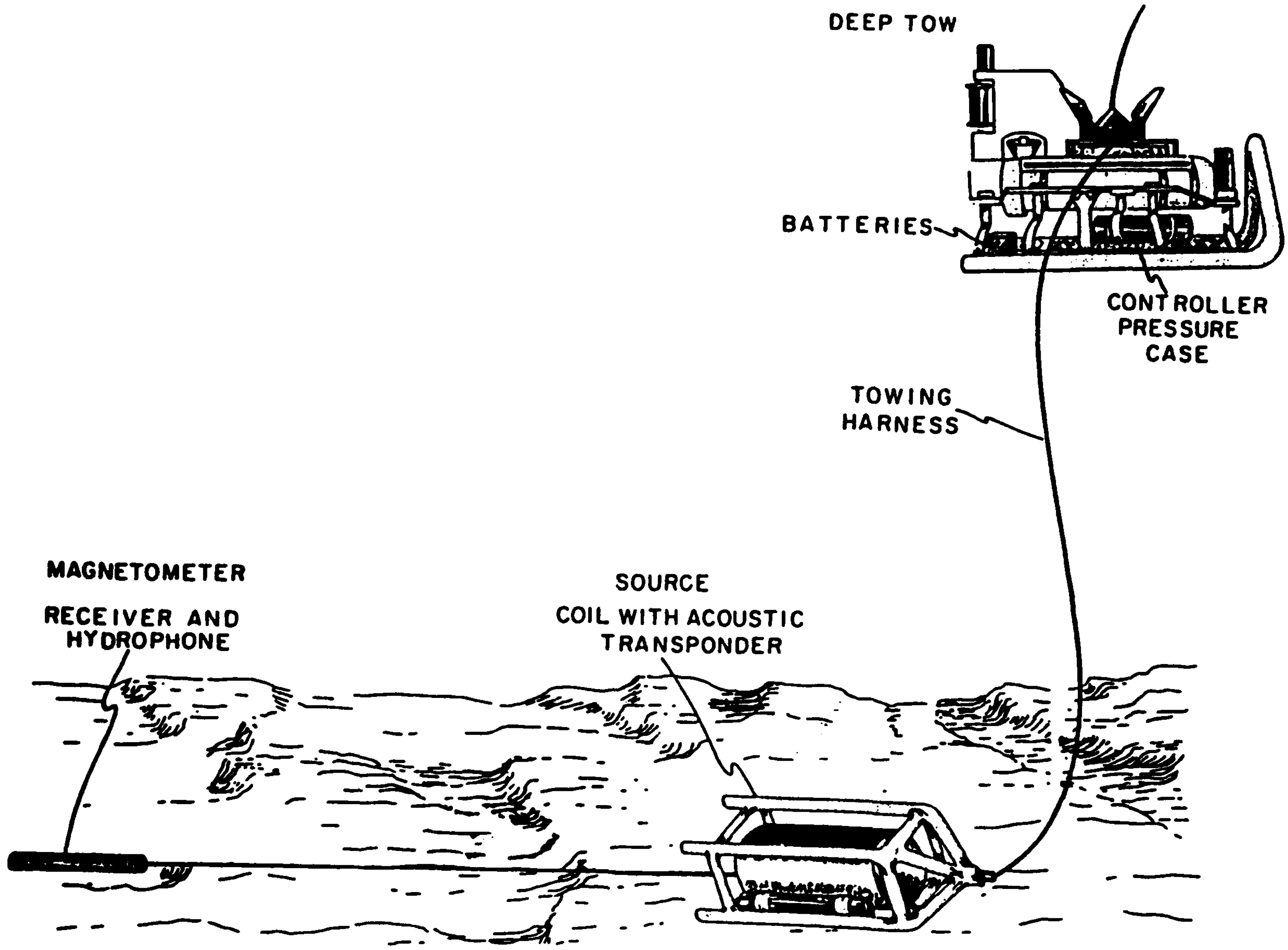

Figure 4. Schematic diagram showing a prototype horizontal magnetic dipole time-domain controlled EM source and horizontal magnetic field receiver designed to be towed along the seafloor behind a Deeptow vehicle. The distance between the source and receiver is determined acoustically.

would be predicted by field studies far from the coastline. There are numerous suggestions in the Soviet literature of terrogenic effects on the ionosphere, in which the earth's electrical structure influences the magnitude and direction of ionospheric current flow. Many of these reports are associated with coastlines. This would introduce short spatial scales into the external sources, further complicating the induction problem from an interpretational and applications viewpoint. Such reports need verification, but certainly deserve attention.

While the current concentration caused by shallowing of the ocean is readily calculable from the known bathymetry, this is only a fraction of the coastline effect. Very little information is available about the large scale electrical structure beneath continental shelves which has a comparable EM effect to changes in water depth. To obtain such data, it is necessary to collect long magnetotelluric lines across the continental shelf, including extension onto land and the deep seafloor. At present, only one such transect is available, the EMSLAB line in central Oregon which straddles an active margin (Figure 5). For technical reasons that can now be overcome, the EMSLAB profile does not include actual measurements on the continental shelf, hence is only able to partially address the important questions. It is known that active margins are underlain by a wedge of recently accreted sediment and seafloor materials, but the extent of the conductivity of the wedge and underlying sutures is not known. Active hydrologic and metamorphic processes are a common feature of active margins, but the subsurface extent of their influence is not characterized because conventional geophysical techniques are comparatively insensitive to metamorphic and circulating fluid effects. Figure 6 gives a qualitative indication of the extent of current concentration in the EMSLAB area.

No transect comparable to EMSLAB exists for a passive margin, but it is certain that the electrical structure, and hence the extent of current concentration, will be categorically different from that in Oregon. For example, passive margins are underlain by continental rocks and volcanics associated with ancient rifting. It is not known if such features on the continental shelves have a major electrical expression, but given the large EM anomalies associated with old rift sutures, it is quite probable that they do. Techniques and instrumentation currently exist to address continental margin electrical structure, and there is certainly strong interest in such basic research problems by both the EM and general geophysics communities.

There is no question but that EM transects similar to EMSLAB are exciting basic science. The continental shelves are currently the focus for many basic geophysical studies, principally using multichannel seismic techniques. A better understanding of continental shelf structure has implications for models of continental breakup and rifting as well as resource (i.e., petroleum) assessment. Informal academic consortia are being organized to coordinate multichannel seismic lines across North American continental margins. Concurrent EM transects at some of these sites would help address basic issues in continental margin structure and rifting mechanisms. EM methods are sensitive to different physical properties of the earth than seismic waves, hence the combination of EM and multichannel seismics is in principle much more powerful than either method taken by itself. At the present time, an informal consortium of academic investigators is planning an EM profile in the southeastern US that will be coincident with a very high quality offshore seismic line. This sort of experiment can offer strong support to Navy-relevant problems, and deserves more attention from ONR.

A final area in which very little information is currently available concerns interactions between the large scale electric currents induced by the ionosphere and small scale conductivity inhomogeneities in the shelf. It is probable that the enhanced electric currents flowing over and under the continental shelves will excite small scale electric currents in inclusions within the

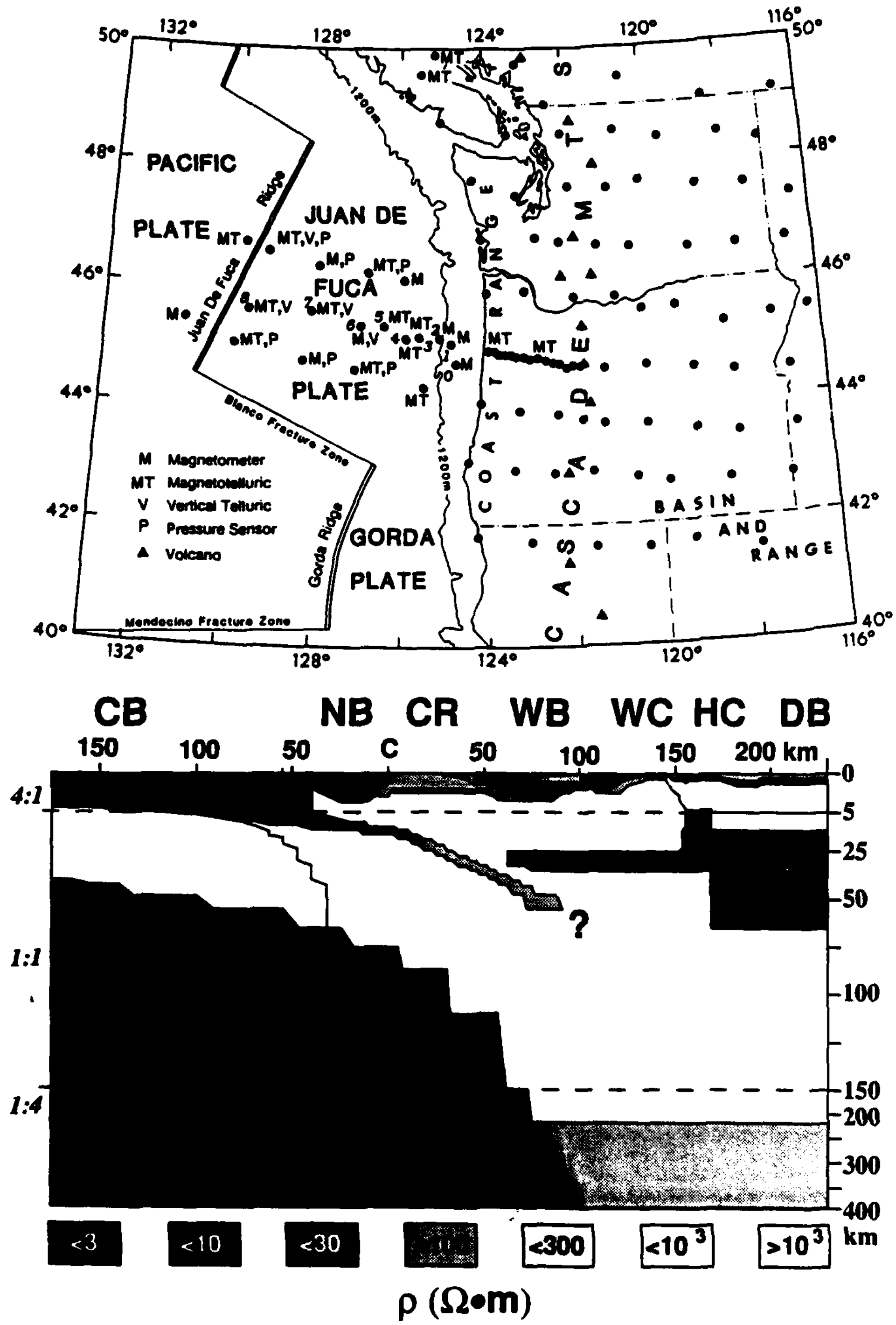

Figure 5. (Top) Location of the EMSLAB experiment in the Pacific Northwest. The densely-sampled main east-west transect is located in north-central Oregon and spans the area from the Juan de Fuca Ridge across the Oregon coast and to the east of the Cascade Mountains. (Bottom) An east-west two-dimensional resistivity cross section constructed from magnetotelluric soundings across the main EMSLAB transect. Note the changes in vertical exagerration at 5 and 150 km depth. The main physiographic provinces are listed at the top and include the Cascadia Basin (CB), Newport Basin (NB), Coast Range (CR), Willamette Basin (WB), Western Cascades (WC), High Cascades (HC), and Deschutes Basin (DB). The main electrical features of this model are the conductive accretionary wedge along the continental slope, a conductive root under the Cascades, and a gently dipping conductive layer extending from offshore to under the Willamette Basin that has been interpreted as the surface of the subducted Juan de Fuca Plate. This model required both onshore and offshore data, and could not have been constructed with either type taken alone (taken from Wannamaker et al., *J. Geophys. Res.*, *94*, 14127–14144, 1989).

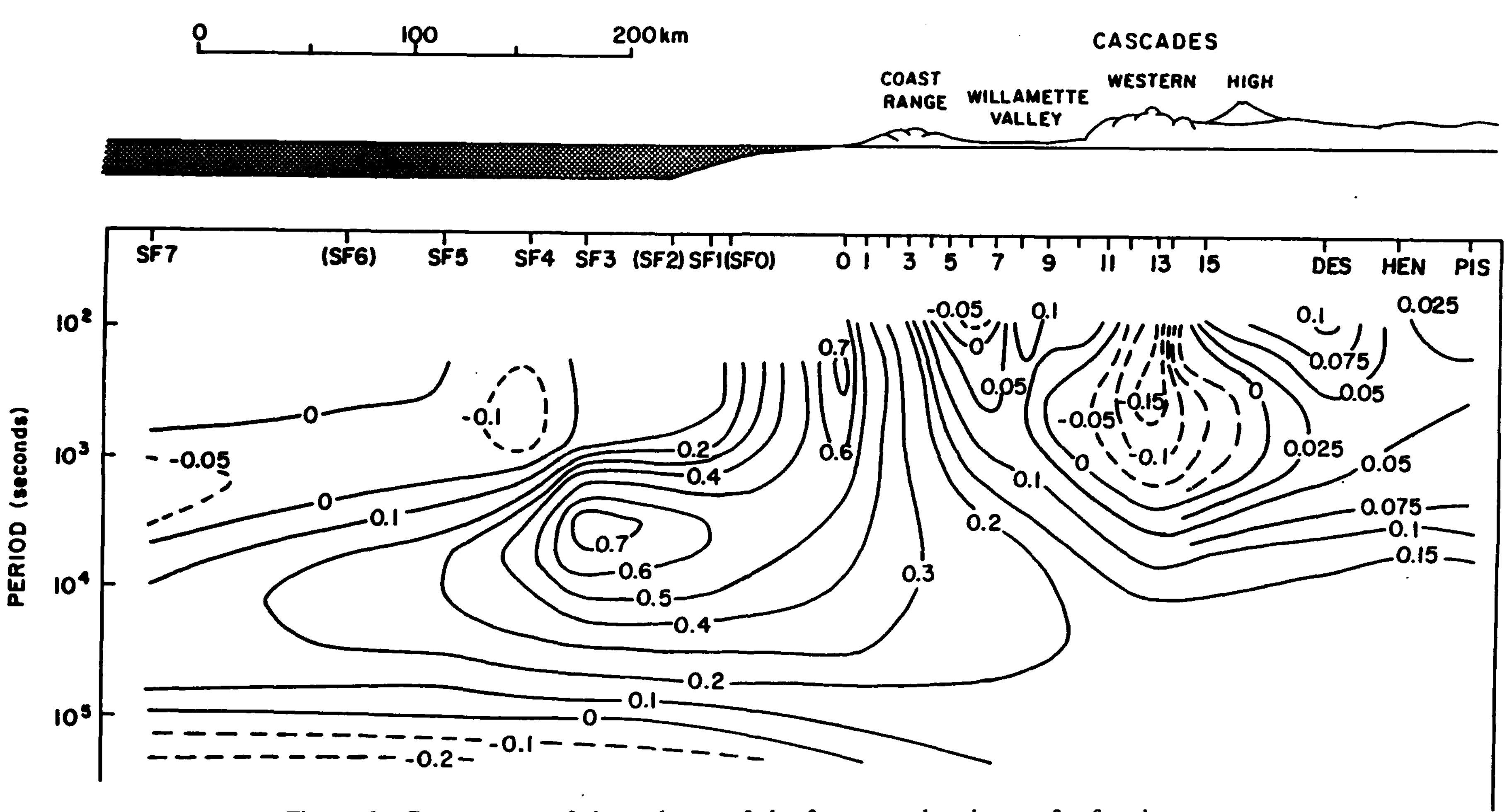

Figure 6. Contour map of the real part of the frequency domain transfer function between the vertical and east magnetic fields along the EMSLAB line. The ordinate is the period in seconds, while the abscissa shows the location along the main EMSLAB transect with major physiographic features sketched Note the strong enhancement of the vertical field at intermediate periods seaward of the continental shelf; the transfer function is zero in the absence of lateral contrasts in conductivity as seen at the extreme left. Seafloor data were not collected on the continental shelf or at periods below a few hundred seconds, so continental shelf enhancement of the vertical field is not resolvable.

seafloor. Without information on the electrical granularity of the shelf, detailed consideration of this problem is little more than speculation. However, it could have important implications for naval applications, especially for airborne EM where the result is comparable to that from variable magnetization of the seafloor.

IV. Recommendations

It should be clear from the discussions of the previous section that there are many basic questions about the EM environment on the continental shelves that cannot be answered without collecting real data. It is also obvious that some fundamental geophysical and oceanographic problems exist in this area, and that EM experiments to address them will yield timely and exciting science. However, at the present time there is no single group within ONR with responsibility for considering geomagnetic problems. Work in the ionospheric and magnetospheric physics area is handled by the Electronics Division. The Environmental Sciences Directorate has focussed the bulk of its resources and attention on acoustics. Other parts of ONR (e.g., Codes 113 and 12) have current interests in nonacoustic ASW that bridge the gap between basic and applied research and which are in need of the fundamental environmental research and data discussed in this report.

Because of this fragmentation and due to the importance of EM problems to the Navy, the first recommendation of this workshop is

- *The Office of Naval Research should initiate a measurement-based, multidisciplinary research program to understand the EM environment of the oceans, with emphasis on the shelves. The major components of such an effort include:*
    1. *Studies of the externally-induced EM fields at the earth's surface with the intent of improving our understanding of their temporal and spatial variability, leading to insight into the nature of the sources.*
    2. *Studies of motionally-induced EM fields and their hydrodynamic sources with the intent of improving our understanding of their scales and origin.*
    3. *Experiments to determine the electrical structure of the ocean-continent transition on both small and large scales at active and passive margins.*
    4. *Studies of the interactions of natural EM fields with such structures.*

The widely scattered nature of the programs within ONR that are concerned with EM have already been noted. Because this field is multidisciplinary and emerging as an important one (both to the Navy and to basic geophysics), it is important that ONR program managers stay abreast of developments in several areas. As a result, the second recommendation of the workshop is that

- *ONR should appoint a scientific advisory group on EM phenomena to represent the many disciplines that must be included in such a research program.*

This committee might simply provide continuing input to ONR regarding important developments in the field, or could help formulate field programs and provide technical guidance in the event that a focussed program of research is initiated.

Finally, the success of a future research program would be greatly enhanced by regular communication between the participants as well as the rest of the EM geophysics community. This is especially true for an effort which covers several fields. The final workshop recommendation is that:

- *ONR should fund a yearly workshop to foster cross-disciplinary fertilization between these areas and to facilitate rapid dissemination of basic research results to scientists and engineers engaged in applying EM techniques to naval problems.*

This should include selected researchers who are involved in EM geophysics research from both academia and Navy laboratories. The workshop would facilitate rapid dissemination of results between participants, but also would enable cross-disciplinary efforts to be carried out. It would also be an important avenue for the applied research and development community to communicate its needs to basic research groups, and for the results of basic research to be obtained by the applied research and development community.

Appendix A
Steering Committee Membership

Prof. John R. Booker
Geophysics Program AK-50
University of Washington
Seattle, WA 98195

Dr. Alan D. Chave (chair)
AT&T Bell Laboratories
600 Mountain Ave.
Murray Hill, NJ 07974

Prof. Charles S. Cox
Scripps Institution of Oceanography A-030
La Jolla, CA 92093

Dr. Patricia L. Gruber (local organization)
AT&T Bell Laboratories
1201 S. Hayes St.
Arlington, VA 22202

Dr. Lynn W. Hart
Applied Physics Laboratory
The Johns Hopkins University
Laurel, MD 20707

Prof. H. Frank Morrison
Dept. of Engineering Geosciences
University of California
Berkeley, CA 94720

Mr. John G. Heacock (ONR liaison)
Office of Naval Research Code 1125
800 N. Quincy
Arlington, VA 22217

Dr. David Johnson (ONR liaison)
Office of Naval Research Code 1243
800 N. Quincy
Arlington, VA 22217

Appendix B
Workshop Attendees

Dr. Ken Allen
Applied Physics Laboratory
Johns Hopkins University
Laurel, MD 20707

Dr. James A. Austin
Institute for Geophysics
University of Texas
8701 Mopac Blvd
Austin, TX 78759

Mr. William Avera
Naval Oceanic and Atmospheric Research Laboratory, Code 352
Bay St. Louis, MS 39529-5004

Prof. John R. Booker
Geophysics Program AK-50
University of Washington
Seattle, WA 98195

Dr. Anthony B. Bruno
Naval Underwater Systems Center, Code 41
New London, CT 06320

Dr. Alan D. Chave
AT&T Bell Laboratories
600 Mountain Ave.
Murray Hill, NJ 07974

Prof. Charles S. Cox
Scripps Institution of Oceanography A-030
La Jolla, CA 92093

Prof. R. Nigel Edwards
Department of Physics
University of Toronto
Toronto, Ontario M5S 1A7
CANADA

Dr. Gary Egbert
School of Oceanography
Oregon State University
Corvallis, OR 97331

Dr. Jean H. Filloux
Scripps Institution of Oceanography A-030
La Jolla, CA 92093

Dr. Antony C. Fraser-Smith
STAR Laboratory
Stanford University
Stanford, CA 94305

Dr. Walter Grabowski
AT&T Bell Laboratories
1201 S. Hayes St.
Arlington, VA 22202

Dr. Arthur W. Green
US Geological Survey
Denver Federal Center
Box 25046
Denver, CO 80225

Dr. Patricia L. Gruber
AT&T Bell Laboratories
1201 S. Hayes St.
Arlington, VA 22202

Dr. Phyllis Greifinger
R&D Associates
PO Box 9695
Marina del Rey, CA 90295

Mr. Charles C. Hanna
NAVAIR AIR-933B
Room 450 JP1
Washington D.C., 20361-9330

Dr. Lynn Hart
Applied Physics Laboratory
Johns Hopkins University
Laurel, MD 20707

Mr. John G. Heacock
Office of Naval Research, Code 1125
800 N. Quincy
Arlington, VA 22217

Dr. James Heirtzler
NASA/Goddard Space Flight Center, Code 622
Greenbelt, MD 20771

Dr. John A. Hildebrand
Marine Physical Laboratory A-005
Scripps Institution of Oceanography
La Jolla, CA 92093

Dr. William J. Hinze
Department of Earth and Atmospheric Sciences
Purdue University
West Lafayette, IN 17907

Mr. Bart Hoekstra
Systems Planning and Analysis, Inc.
5111 Leesburg Pike, Suite 200
Falls Church, VA 22041

Prof. George Jiracek
Department of Geological Sciences
San Diego State University
San Diego, CA 92182

Dr. David Johnson
Office of Naval Research Code 1243
800 N. Quincy
Arlington, VA 22217

Dr. G. Leonard Johnson
Office of Naval Research Code 1125
800 North Quincy
Arlington, VA 22217

Mr. Gracen Joiner
Office of Naval Research Code 1114SP
800 North Quincy
Arlington, VA 22217

Dr. Richard Joseph
Dept. of Electrical and Computer Engineering
The Johns Hopkins University
Baltimore, MD 21218

Dr. Louis J. Lanzerotti
AT&T Bell Laboratories
600 Mountain Ave.
Murray Hill, NJ 07974

Dr. Douglas S. Luther
Scripps Institution of Oceanography A-030
La Jolla, CA 92093

Prof. Theodore Madden
Dept. of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. Edward Mozley
Naval Oceanic and Atmospheric Research Laboratory, Code 352
Bay St. Louis, MS 39529-5004

Mr. Edward Nichols
Department of Engineering Geosciences
University of California
Berkeley, CA 94720

Mr. Warren Payton
Naval Air Development Center Code 5012
Warminster, PA 18974-5000

Mr. John Scarzello
Naval Surface Warfare Center Code R43
10901 New Hampshire Ave.
Silver Spring, MD 20903-5000

Dr. Adam Schultz
School of Oceanography WB-10
University of Washington
Seattle, WA 98195

Dr. Thomas J. Shankland
MS D447
Los Alamos National Laboratory
Los Alamos, NM 87545

Ms. Elizabeth Squires
AT&T Bell Laboratories
1201 S. Hayes St.
Arlington, VA 22202

Dr. Pascal Tarits
Laboratoire de Geomagnetisme
Institut de Physique du Globe
4 Place Jussieu
F-75252 Paris Cedex 05
FRANCE

Dr. Spahr Webb
Marine Physical Laboratory A-005
Scripps Institution of Oceanography
La Jolla, CA 92093

Dr. Larry Zanetti
Applied Physics Laboratory
Johns Hopkins University
Laurel, MD 20707

Appendix C
Plenary Session Agenda [Start Time]

I. Registration and Coffee/Doughnuts [0830]

II. Introduction and Navy Relevance Issues
   A. Welcome (A. Chave, ATTBL) [0900]
   B Meeting Purpose and Organization (J. Heacock, ONR) [0905]
   C. Introduction (J. Heacock, ONR) [0910]
   D. SSBN Security Program Overview (L. Hart, JHU/APL) [0920]
   E. ASW Program Overview (D. Johnson, ONR) [0935]
   F. Technical Aspects (L. Hart, JHU/APL) [0950]
   G. Discussion [1020]

III. Sources of EM Fields
   A. Magnetospheric/ionospheric (L. Zanetti, JHU/APL) [1050]
   B. Atmospheric/manmade (A. Fraser-Smith, Stanford) [1120]
   C. Discussion [1150]
   D. Lunch break [1220]
   E. Oceanic (S. Webb, Scripps) [1300]
   F. Discussion [1330]

IV. Interactions with the Earth
   A. Structure of Continental Margins (J.A. Austin, UT Austin) [1400]
   B. Electromagnetic Effects at Coastlines (C. Cox, Scripps) [1430]
   C. Break [1500]
   D. Controlled Source Measurements (R.N. Edwards, U of Toronto) [1515]
   E. Physical Principles of Rock Conductivity (T. Shankland, Los Alamos) [1545]
   F. Discussion [1605]

V. Charge to working groups [1650]

Appendix D
Ionospheric Working Group Report

L.J. Lanzerotti (chair), G.D. Egbert, A.C. Fraser-Smith,
P. Greifinger, T.R. Madden, E.A. Nichols, L. Zanetti

The sources of electromagnetic fluctuations in the frequency band $\approx 10^{-3}$ to $\approx 10^{3}$ Hz at the ground and sea level is presently understood as outlined in Figure 7. In the following sections, these various sources are each briefly discussed and comments are made regarding present understanding of the sources and their spatial and temporal characteristics.

The details of the morphology of the overall spectral characteristics of magnetic and electric field fluctuations in the entire range 10^{-3} to 10^{3} Hz are not known. Spectra covering this frequency range do not exist. Such statistical information would provide deeper understanding of the time and space variations (if any) of such fluctuations and would yield greater confidence as to the instrumentation characteristics required for scientific investigations of this band. Such information would also provide insights into the causes and sources of these fluctuations in the magnetosphere and ionosphere.

A. Hydromagnetic waves (10^{-3}-10^{-1} Hz). Collective plasma effects in the earth's magnetosphere in the frequency range from $<10^{-3}$ to $\approx 10^{-1}$ Hz are often produced by hydromagnetic waves. These waves produce changes in the ionospheric current systems which are detectable on the earth's surface as magnetic field fluctuations (geomagnetic pulsations). Over the last two decades, a large body of open literature has resulted from spacecraft and ground-based research targeted at understanding the genesis and sources of these waves, and thus at characterizing morphologies–local time, seasonal, latitudinal, etc. distributions. Substantial information exists as to the larger-scale azimuthal and latitudinal spatial (several hundreds of km) and temporal (few seconds to hours) distributions of these waves, particularly their amplitudes, polarizations, phases, etc. The latitude dependence of these waves on the earth's surface are often dominated by one or several (overlapping) "resonances". However, at spatial distances of the order of 100 to 200 km, coherence and spatial scales are poorly characterized except perhaps in one or two specific locations. Gradients in these parameters for hydromagnetic waves are expected to be strongly latitude dependent and of particular significance at auroral and magnetospheric cusp latitudes. Of most significant research interest are the azimuthal scale sizes, both temporal and spatial, of hydromagnetic waves at all local times and under different levels of geomagnetic activity. Accurate determinations of azimuthal propagation directions, velocities, and spatial scale sizes would yield important new information about the sources.

Rather extensive, largely statistical, research on hydromagnetic waves and their relationships to interplanetary (solar wind) conditions and to magnetic storms over the last two decades indicate that some predictability of wave occurrence on a large scale is achievable. For example, it is highly likely that waves in the period band $\approx$20-40 s will be observed throughout the dayside magnetosphere if the interplanetary magnetic field has a predominantly radial orientation with respect to the magnetopause. However, the predictability of specific amplitudes at a given frequency over specific areas is not possible at present. Needed are more detailed case studies of wave generation by specific interplanetary conditions in order to better understand the physical processes at the magnetopause.

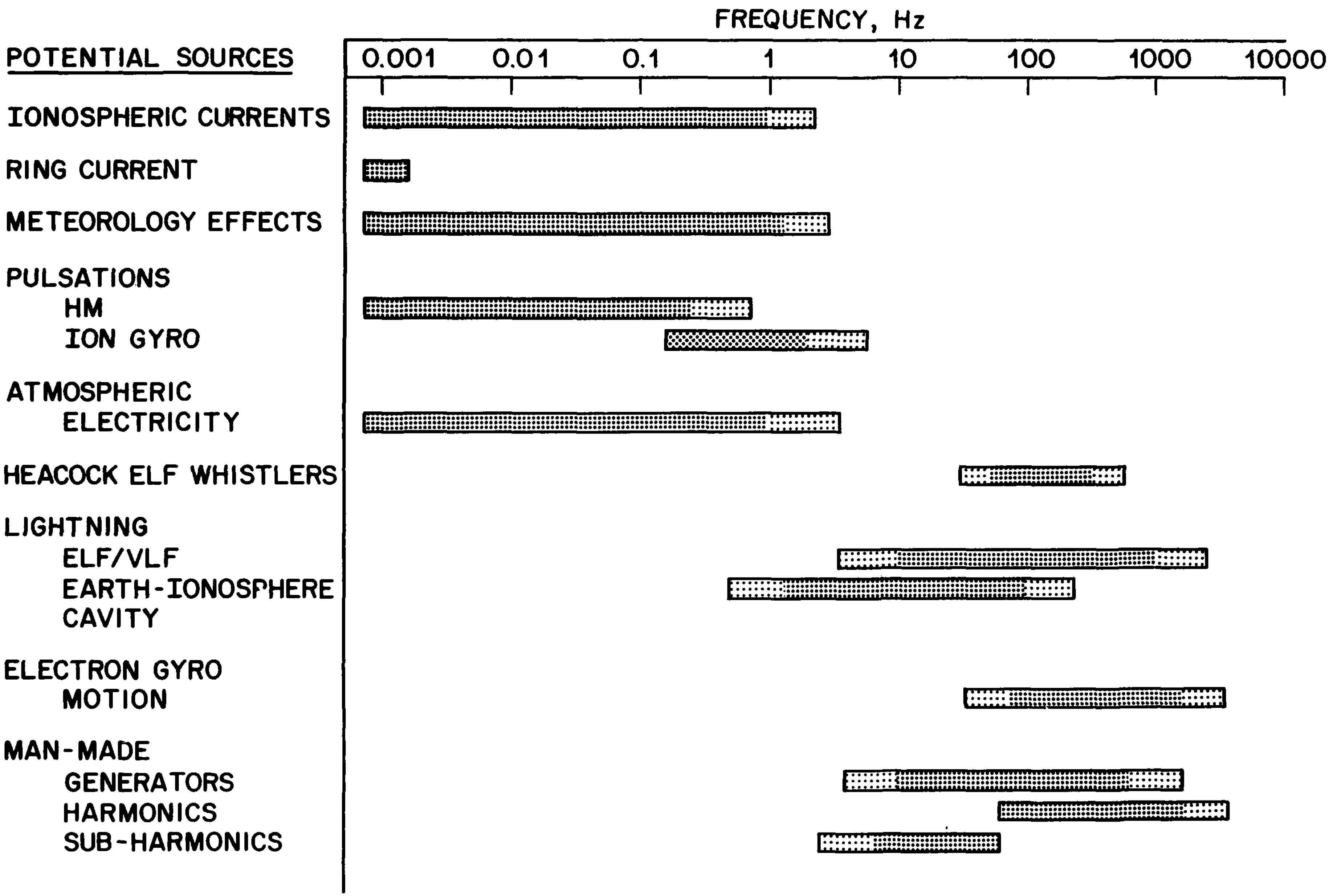

Figure 7. Bar chart showing the frequency ranges where different ionospheric sources will be important.

B. Ion-Cyclotron Pulsations (0.2-5 Hz). The origin and morphology of these signals is moderately well understood, but there are still some questions regarding the sources. In particular, their location does not always appear to agree with the predictions of the theoretical models. The signals are very coherent over the distance scales of interest. Their predictability is helped by their tendency to occur 2-7 d after the start of a magnetic storm. The reasons for this are not understood. In addition, knowledge of their specific areas of occurrence is quite poor. Within the above frequency range it is impossible to predict the specific frequencies of occurrence. In other words, while there is reasonably good general statistical information on these pulsations, specific data pertaining to when and where an individual pulsation event will be observed is lacking. Improvements in this understanding would provide significant new ways of mapping magnetosphere plasma conditions.

There is some recent evidence for a relationship of certain frequencies with the presence of He ions in the magnetosphere. These ions may also be significant to magnetospheric propagation of the ion pulsations. These relations have not been studied extensively.

Ion-cyclotron-generated signals propagate from high to low latitudes via an F-region waveguide; while the physics of this propagation is well understood, its parameters still need further definition. The transition, or coupling, from left hand polarized field line propagation to right hand waveguide propagation involves several complicated mechanisms that have not received adequate study. As a result, it is not possible to quantitatively predict the transfer of energy from the magnetospherically propagating waves into the waveguide propagating waves.

C. Electron-Cyclotron Radiation (10-1000 Hz). Although most of the background noise at a specific locale in the ELF and VLF bands is dominated by sferics from lightning and power line harmonics, there are occasions when magnetospherically-generated noise (hiss, chorus) can be seen, particularly at high latitudes. It is thought that this noise is generated predominantly by electron-cyclotron radiation, but there are other generation and propagation effects that appear to be effective in giving the noise its particular spectral characteristics.

Hiss, or more specifically broadband auroral hiss, can sometimes occur with great intensity over essentially all of the ELF and VLF bands. At such times this hiss is larger than all other forms of activity. Very occasionally this noise can be intense enough to dominate the frequency band in which it occurs. Unfortunately, the occurrence statistics and other properties of this broadband hiss are poorly known. It is highly desirable that measurements be made to provide more information about this hiss. It would be particularly interesting in the context of both science and applications to know more about the lowest frequencies reached by this noise and the scale size of the generation regions.

As noted above, the electron-cyclotron radiation has a strong latitude dependence (with a peak in the auroral zones), but the latitude dependence is not known in detail. Further, its spatial coherence is very poorly known. Acquisition of such knowledge would yield information on the source processes and their scales.

Almost all interpretations of low-frequency electromagnetic wave propagation in the upper atmosphere involve ducted propagation of the waves, yet little is known about these ducts. It has been hypothesized that they are linked to lightning, but there is little evidence to support this idea. More research directed toward obtaining a better understanding of the formation of these ducts and their distribution in the magnetosphere is of considerable scientific interest.

D. ELF Whistlers (100-300 Hz). This unusual phenomenon, which has only been reported by R. Heacock in the Alaskan auroral zone, represents a possible new form of electromagnetic noise in the 100-300 Hz band. Clearly, it is not a major noise form, but the fact that its existence cannot easily be explained by current theory makes more study desirable. Some experimental effort to confirm or disprove the existence of this phenomenon and a similar theoretical effort to see if it can be fitted into the present theory covering ELF and VLF waves in the magnetosphere is recommended.

E. Lightning (1-1000 Hz). Lightning is the primary source of electromagnetic noise at and above the ground, and to a comparatively small depth into the ground, in the 1-1000 Hz range. The statistical distribution of lightning over the surface of the earth is fairly well known and in the US it is monitored in real time. The distribution is highly variable both in space and time and cannot easily be predicted. Better characterization of the spatial scales of ground discharge would provide insights into the scale sizes of cloud electrification processes.

The cloud-to-cloud component of lightning activity is not as well understood or monitored as is the cloud-to-ground component, but is not as scientifically significant in the present context due to the usually low amplitude of the radiated signals near the ground. One gap in our knowledge is the link between the electromagnetic radiation from what can be referred to as a lightning event (single and/or multiple cloud-to-ground strokes) and the effective time-varying current source(s) in the frequency range of interest. The issue is not propagation, but source current characterization. Experiments to measure the electromagnetic fields near lightning events that will enable the source and propagation effects to be separated are recommended.

F. Earth-Ionosphere Cavity Resonances (7-80 Hz). The earth-ionosphere cavity resonances are excited by the worldwide distribution of lightning and they are basically understood and comparatively weak. Further studies of these resonances do not appear to be necessary at this time.

G. Meteorological Ionospheric Currents. The ionospheric electrical current system associated with ionospheric winds is well known to be the source of the Sq signal, but much less is known about the contribution of this system to shorter period electromagnetic signals. Such signals could arise from smaller scale features of the wind system such as atmospheric gravity waves and modulation of the conductivity of the ionosphere by particle precipitation events. The correlation distance for such signals would be long simply because of the height of the ionosphere. The panel was unable to identify any known examples of such signals other than effects associated with nuclear explosions (e.g., the Starfish experiment produced such large magnetic variations in the 1-10 s period range on the opposite side of the earth from the explosion that one panel member's attempts to record the signals could only identify the zero crossings), but given that the Sq signal is one of the largest background signals, one would not be surprised if significant background noise at much shorter periods could be produced by such ionospheric phenomena.

H. Atmospheric Electricity. The electrical system that is associated with lightning phenomena can also make other contributions to the ground (horizontal) electric fields that are comparable in amplitude to the usual background field. These effects are associated with cloud motions, but the panel is unaware of any significant studies of that effect. Because such signals are locally generated, they have much smaller correlation distances than the usual background field (i.e., one would expect correlation distances to be in the 1-10 km range). Studies of the spatial and temporal variability of the atmospheric electric field are very pertinent to the problem of understanding the sea level electric field noise spectrum.

I. Ionospheric Current Systems. Large scale electric currents in the earth's ionosphere will produce distant magnetic signatures in the 10^{-3} to 10^{-1} Hz frequency range. The scale size of these currents os 5°-10° of latitude in the north and south auroral zones (on average, continuous ovals or circles of about 15°-20° radius centered on the magnetic poles, and a function of geomagnetic activity). The currents are comprised of pairs of oppositely-directed field-aligned (Birkeland) sheets usually connected with a horizontal ionospheric current (Pedersen current) in the direction of the large-scale electric field. The other horizontal ionospheric current is a Hall type (auroral electrojet) in the **E**×**B** direction, the most detectable magnetic signature from the ground. Edge effects of the Birkeland-Pedersen "solenoidal" current are also detectable. Historically, the Hall currents have been observed since the beginning of ground magnetic observations while the Birkeland currents were confirmed only by spacecraft measurements about two decades ago.

The large scale current systems are statistically well known from both low latitude spacecraft and ground-based magnetic measurements. Both the latitude and local time distributions have been characterized. The Birkeland system's intensity is found to be (statistically) highest in the dayside sector; the current densities are typically 1-5 $\mu A/m^2$. The integrated current of this system is approximately aligned with the v×**B** of the solar wind when **B** is directed southward and is reasonably predictable, again on a global scale. If the **B** is strong and pointed northward, the auroral zone currents diminish and are replaced with similar density current systems contained within the polar cap (<15° latitude from the pole). Auroral electrojet Hall currents are co-located with the Birkeland-Pedersen system and are generally electrodynamically self-consistent.

Specific temporal and spatial effects of the ionospheric current systems are not as generally well known; in particular, edge effects on the order of 100 km in extent will be observable at high and possibly mid latitudes. Thus, predictions at specific geographic locations of these disturbances are difficult at this point, but retrospective analysis of present magnetic field data during specific phases of geomagnetic activity could be related to latitude and local time.

The equatorial ring current produces an equatorial and mid-latitude depression of **B** and is reasonably well-characterized and monitored by ground magnetic observatories.

Spatial scale sizes on the order of auroral arcs (>1 km) are accompanied by electrodynamically consistent Birkeland and Hall currents. These systems can move during geomagnetic storms by some 5° per minute. In addition, there also exist ionospheric current systems associated with pulsating aurorae with intrinsic frequencies as high as 1 Hz. The above are confined to high latitudes and are not coherent on the 100 km scale size of interest.

There are strong solitary Birkeland, Pedersen, and Hall filamentary structures around local noon in the cusp region (≈75°-85° magnetic latitude). These structures provide out-of-phase transverse and parallel magnetic signatures of ≈100 km to ≈200 km scale length and are often single pulse in nature. These events were only recently identified, are not well characterized, and are not predictable with our present state of knowledge; neither are they easily monitored at a particular geographic location. Studies of these high latitude phenomena can provide new information on processes occurring at the magnetopause, a hot area of current research activity.

J. Other Phenomena. This category allows for phenomena not included in the traditional ionospheric sources. The panel discussed the possibility of the modulation of other ionospheric source systems, such as the auroral electrojet, by human-made sources (e.g., the EISCAT heater and the Alaskan MW radars). This mechanism could launch EM energy into the observed frequency range of 1 Hz to 1 kHz.

Another mechanism could be induced changes in ionospheric conductivity caused by electron precipitation. The monitoring of VLF signals and lightning by a Stanford group seems to suggest that such an effect may occur.

Another possible mechanism that has not been monitored is the spatial and temporal distributions of high frequency (1 Hz to 1 kHz) ionospheric currents. A large spatial distribution of coherent high frequency energy may be an EM source as well in this band, although its significance at ground level is likely to be slight.

The panel concluded that higher power line harmonics are significant in the ELF/VLF band, but are well understood. However, the reasons for occasional occurrence of subharmonics are not understood at all. The generation of lower beat frequencies (i.e., 50 Hz and 60 Hz) caused by nonlinear phenomena does occur. For example, nonlinear resistive elements may cause beat frequencies to appear such that 50 and 60 Hz power grids will generate a 10 Hz signal.

Several Soviet experiments and some US laboratory work suggests that high frequency EM energy in the range of hundreds of Hz to hundreds of kHz is observed in association with some earthquakes, although the source and propagation mechanisms are highly speculative.

Nuclear explosions locally produce EM signatures but have also caused larger scale ionospheric changes.

Cultural clutter (e.g., electric railways) have coherent correlation lengths that are observable.

K. Analysis of Array Data. Some analysis of data from small magnetometer arrays (5 stations, 10-200 km total array size) collected in association with the EMSLAB experiment has revealed a high degree of spatial coherence of the source fields in the 10^{-4} to 10^{-2} Hz range (e.g., squared coherence of ≈0.999 at 10^{-4} Hz and ≈0.98 at 10^{-2} Hz, with the higher frequency more affected by instrument noise). These results at a single location leave a lot of open questions, including 1) extension to higher frequencies, 2) coherence at larger spatial scales, 3) variability of coherence characteristics on a variety of time scales, and 4) extension to higher and lower latitudes.

There is a lot of existing ground-based data which could be assembled and reanalyzed to produce a more complete picture of the frequency, time, and latitude dependence of spatial coherence of external EM sources. This would be very relevant to fundamental science questions as well as to Navy needs. One particular area where there is a necessity for research is in time series/stochastic process modeling of the source fields as measured at the earth's surface. The signals are highly non-stationary and non-Gaussian spatio-temporal processes and they need to be characterized by methods which can localize in time and space or frequency and wavenumber. For instance, a complete characterization of the spatial and temporal aspects of the spatial coherence of sources requires more than a spectrum which of itself only characterizes the long-term average behavior of the contributing sources. This is clearly not enough to characterize the true physical situation. Better methodologies to describe "typical" source behavior are needed.

L. A Possible Research Program. As an initial step toward gaining further understanding of ionospheric and magnetospheric sources, attention should be paid to investigating magnetic data (in digital form) which may exist from past projects that were carried out for other purposes. The analyses of sets of even two or three magnetometer stations spaced within 100 to 200 km on land would provide important scientific results and point the direction toward needed additional work.

At next highest priority, a set of experiments on the earth's surface at different geomagnetic latitudes consisting of magnetic measurements in the range from DC to ≈10 Hz should be carried out. The instruments should be spaced at 100 km intervals over a 200 km, approximately square, array for a total of nine instruments. The measurements would be collected at low (e.g., Florida), middle, subauroral, auroral, and polar cap latitudes. The instrumentation elements could be moved from one latitude to another if resources were insufficient to support more than one operational array at a time. However, measurements at each array location should be carried out for at least a year, and probably longer.

The scientific objectives to be pursued would depend upon the geomagnetic locations of the arrays and the frequency range to be examined. For example, no information on spatial scales exists at high (≈75°) geomagnetic latitudes. This is of high research priority. Of most importance are the "m-numbers" (i.e., the integer azimuthal wavenumber index in $e^{-im\phi}$, where ϕ is longitude) of hydromagnetic waves and ther dependence on dayside magnetic field fluctuations corresponding to interplanetary conditions. The group velocity of wave propagation could be determined as well. These parameters would provide constraints on source processes; high velocities (order 10 km/s) accompanied by relatively small m-values would tend to favor a Kelvin-Helmholtz instability source, whereas smaller velocities (order a few km/s) and larger m-values might indicate another source mechanism, such as magnetic reconnection-driven waves.

At auroral latitudes, some Bell Laboratories work suggests that the azimuthal extent of hydromagnetic waves is larger than at geomagnetic latitudes of ≈75°, corresponding to the dayside cusp region. This needs further checking, and the velocities of propagation of the waves to wider azimuthal extents needs determination. This would also give additional discrimination between internal and external source processes at auroral latitudes. Ground-based research can contribute uniquely to such problems as these in as much as there are not likely to be opportunities to have a fleet of azimuthally-spaced spacecraft in localized latitudinal regions of the magnetosphere.

Array studies of ≈1 Hz waves in the region of the plasmapause (approximately 3 earth radii altitude at the equator) would provide better constraints than presently exist on the plasmapause as an important ion cyclotron wave source. Ionospheric ducting at these frequencies could make source determinations from one or two station measurements quite difficult. While synchronous spacecraft measurements have given unique insights to the question of these waves at ≈5.5 earth radii altitude, the effects of a large plasma density gradient on wave sources are undetermined. Theoretical considerations clearly show that large plasma density discontinuities will stimulate and exchange wave growth due to the ion cyclotron instability of the trapped protons. Hence, a set of array data in this geomagnetic region would significantly improve present knowledge of these waves and their generation conditions (geomagnetic activity, solar activity, etc.).

Appendix E
Ocean-induced Fields Working Group Report

S.C. Webb (chair), P.L. Gruber, L.W. Hart, D.S. Luther

Oceanic disturbances can affect electromagnetic measurements in the ocean because natural EM fields are induced by the motion of conducting seawater through the geomagnetic field. We consider here some possible oceanic influences on electromagnetic measurements in the ocean based largely on theory. Finding that there are a paucity of data to constrain the models, we then propose possible experiments in three similar but differing environments which are perhaps most relevant to Navy problems: a "near port" or estuarine experiment, a near shore experiment (at about 10 km from land), and an offshore shelf experiment (10 to 200 km offshore).

Given a model for the frequency-wavenumber spectrum of an oceanic process and some idea of the conductivity structure in the water and under the seafloor, one can in theory calculate the induced EM fields. Many investigators have estimated the electric and magnetic fields induced by surface waves, geostrophic currents, turbulence, and various other oceanic processes. Although the motional induction problem is more complicated in nearshore regions because of conductivity variations under the seafloor and the presence of coastlines, these estimates provide a guide for possible experiments. An early goal of any program should be to review the existing literature and continue calculations of induced EM fields in the ocean when necessary to provide estimates of the relative importance of the many oceanic processes. This must be tied together with some specific information on the nearshore environment and include an examination of the importance of geological and edge effects on induction. Most importantly, it is essential at the outset to obtain some baseline measurements in the field to confirm theoretical estimates of the EM fields. Such data are totally lacking for the continental shelves at present.

A variety of oceanic sources were considered for this report. We first examine internal waves and turbulence together because the physical processes are similar. Internal waves exist throughout the ocean. In deep water, the internal wave spectrum can be described by the Garrett-Munk model spectrum; these produce an electromagnetic signature only in a band below 10^{-4} Hz and are extremely weak. However, the Garrett-Munk spectrum is known to be a poor model for internal waves in the upper ocean, particularly in the mixed layer. Packets of large amplitude internal waves with frequencies near 10^{-3} Hz, wavelengths of 300-1000 m, and phase velocities of order 1 cm/s are often observed in the upper ocean. Near inertial frequency internal waves may have velocities of 30 cm/s or more. Such waves should induce detectable fields, but additional theoretical work is needed to integrate these observations into estimates of the induced EM fields. New measurements will be required to validate the role of internal waves in the shallow water induction problem. Finally, nonlinear solitary internal waves are seen in shallow coastal areas such as the Straits of Juan de Fuca and Massachusetts Bay. These waves can be associated with strong currents (up to 1 m/s), have length scales from 100 m to several km, and intrinsic frequencies from 10^{-3} to 10^{-1} Hz. Theory suggests that the solitary waves will generate sizable EM fields, and the character of the waves suggests that they might be confused with naval targets.

The presence of bottom boundary layers in shallow water suggests that models of turbulence may be useful for estimating induced fields on the shelf. Back of the envelope calculations indicate that bottom boundary layer turbulence may be a strong source of potential noise to seafloor electric field detectors. A model of the frequency-wavenumber spectrum of the turbulent velocity is needed to better estimate the EM contribution from this source. However, direct measurement of the induced EM signals is probably the easiest way to approach the problem of modeling these phenomena since the theoretical frequency-wavenumber spectrum is strongly dependent on local boundary and oceanic conditions. Typical ocean floor velocities associated with turbulence could be up to 1 m/s, the typical length scale will be the boundary layer thickness (10 to 100 m) or the depth of the ocean in shallow water. Characteristic frequencies lie in the 0.01 to 0.1 Hz range.

An organized kind of wind driven mixed layer flow called Langmuir cells may also be a possible source of induced EM fields. Langmuir cells have a spatial scale of 10-150 m in the crosswind direction and may be as large as 1.5 km in the downwind direction with velocities of 1 to 20 cm/s. Such cells may generate detectable fields at fairly low frequencies.

Surface waves are another important source of induced fields. The signals from surface waves have been calculated by many authors over the past two decades. There are a few measurements of swell and wind wave induced fields. Swell and wind waves can generate currents up to a few m/s and range in frequency from 0.05 to above 1 Hz. We have also considered the effects of long gravity waves. Long waves are more efficient at inducing EM fields because of their larger spatial scale, but this must be tempered by the realization that typical wave amplitudes and velocities are much less than the higher frequency wind driven waves. One special case of long period waves are edge waves (shore swash) which can have significant wave heights. Two other special cases of long surface gravity waves are harbor resonances and seiches, both of which can be associated with wave heights of a few tens of cm and periods of a few minutes. Some calculations of the fields generated by these sources are warranted. The relative importance of long waves to the EM measurement program may be enhanced because they can induce fields that are correlated over significant distances due to their long wavelength, and so interfere with noise cancellation schemes. Further work on the effects of seafloor conductivity contrasts and boundaries (coastlines) is recommended for the lowest frequency components of swell and long waves.

Elastic (Rayleigh) waves are the primary source of induced electric fields on the deep sea floor in the band from about 0.05 to 1 Hz. The scales associated with elastic waves may be many kilometers. Seismoacoustic noise will contribute to EM measurements made in shallow water, but it is difficult to estimate the relative importance of this source. Seafloor displacements will be larger in shallow water and non-propagating sources of earth deformation associated with atmospheric and oceanic pressure fluctuations may generate signals both by inducing fields in the water and by moving (electric field) or rotating (magnetic field) the sensors.

Ocean currents on the shelf will be both geostrophic and ageostrophic. Nearly geostrophic shelf waves are typically associated with periods of a few days, alongshore scales of tens to hundreds of km, and currents of a few tens of cm/s. As such, these currents are probably important to the airborne problem as a source which varies on a spatial scale of a fraction of the shelf width in the cross shelf direction. Strong geostrophic and ageostrophic currents are also associated with ocean fronts. Ocean fronts are roughly linear features exhibiting very large gradients in salinity and temperature and strong horizontal shear across the front. Fronts are usually less than a few kilometers wide and may be as narrow as a hundred meters. Strong gradients of the EM field should be associated with these fronts and changes in the position of the front could be associated with rapid changes in the EM fields. Ocean fronts near the coast are frequently associated with "squirts" or large jets of shelf water extending 100 km or more from the coast. The examples of shelf currents above have very low intrinsic frequency and small to large spatial scales. They are important primarily because they will advect smaller scale features past stationary sensors.

A second kind of front will be present in estuaries. Thermohaline fronts occur due to the contrast between the fresh water outflow from rivers and the saline ocean water. These fronts are advected up and down the estuaries by the tides. Large electrical conductivity contrasts are associated with these fronts. The contrast in conductivity between fresh river water and saline ocean water could affect measurements of the geoelectric field, making the cancellation of the ionospheric fields more difficult to achieve. Significant velocities could also be associated with the gravity currents at the advancing front, implying motional induction and detectable fields.

We may consider three possible sites for experiments to test these ideas. Only some of the candidate properties will be important at each type of site. The first experiment should be performed in the offshore part of the shelf far from land. The major processes expected to be important here are surface waves, turbulence, internal waves (including solitons), and possibly seismoacoustics. Geostrophic fronts would also be an interesting target to study. The second experiment should be placed in the nearshore zone which is dynamically similar to the offshore site. In addition to the processes already described for deep water, long period surface waves (edge waves) and organized surf zone currents might become significant. Boundary (coastline) and geological (seafloor conductivity) effects may also be important. A final experiment should be performed in a near port or estuarine environment where nonlinear internal waves may be of greatest significance and thermohaline fronts will influence the measurements. Surface waves and turbulence will also be important and long waves or seismoacoustic signals could be sources of EM signals correlated over large distances. Boundary effects and variations in seafloor conductivity will certainly complicate the interpretation of any of these measurements.

To accomplish these experimental goals, there are three areas where some effort toward the development of new electromagnetic instrumentation would be useful. First, a seafloor magnetometer (probably based on ring core fluxgate technology) suitable for frequencies above 0.01 Hz needs to be developed. Second, a mechanical chopper instrument capable of short baseline electric field measurements above 0.01 Hz would be useful. Finally, further work on electrode technology might yield significantly better electric field measurements. Deep sea electrodes may need to be redesigned to operate in the more complex nearshore regions.

For all of the experiments outlined earlier, the primary instrumentation will be small arrays of both short (a few m) and long (up to a km) baseline electric field instruments and three component magnetometers. The latter should be equipped with tiltmeters to correct for apparent field fluctuations associated with near bottom currents and motion of the seafloor. Short baseline measurements of vertical electric fields may be particularly useful in discriminating between magnetotelluric and ocean-induced fields. In addition to the seafloor EM instruments, small land EM arrays of three component magnetometers equipped with tiltmeters and a few electric field sensors would be useful.

Ancillary environmental measurements will also be needed. These should include sensors to measure ocean currents, surface waves, internal waves, and salinity/temperature fluctuations. The actual suite of measurements will depend on the experimental locale. Most of the auxiliary instrumentation required for these experiments is presently available within the academic community. Internal wave and ocean current measurements can be obtained from moored current meters as well as from bottom mounted, moored, or ship mounted acoustic doppler current profilers. The benthic acoustic stress sensor developed at WHOI would be very useful for measuring bottom boundary layer turbulence at small scales. New acoustic doppler sensors are being developed which can be used to observe Langmuir cells and mixed layer turbulence. Several existing profiling instruments measure internal wave motions within the water column from the motionally-induced electric field. A synoptic picture of the baroclinic current and temperature profile can be obtained from drops of expendable current profilers (XCP) which also use motional induction principles. Profiles of salinity and temperature are routinely obtained using conductivity-temperature-depth (CTD) instruments and a more synoptic picture of the temperature profile can be obtained using expendable bathythermographs (XBT). Surface waves can be measured using wave buoys, arrays of bottom pressure sensors, and current meters.

Appendix F
Large Scale Electrical Structure Working Group Report

J.R. Booker (chair), J.A. Austin, J.H. Filloux, G.R. Jiracek,
P. Tarits, W. Avera, T. Shankland

The continental shelf is the electrical connection between the deep ocean and the continents. A core scientific problem for any attempt to reliably characterize the electromagnetic noise environment on continental shelves is a complete study of the electrical transition from the ocean to the continent. The very large conductivity contrast between seawater and land, as well as major changes in deeper subsurface structure associated with the transition between ocean and continent, strongly concentrate electric currents (largely induced by ionospheric processes) over the continental shelves. These currents, which have periods ranging from seconds to days, are induced in the ocean water over very large scales. From the point of view of naval applications, the electric current morphology changes sufficiently slowly with time to be regarded as stationary, and the conductivity contrast serves mostly to enhance or reduce the ionospheric noise level. This has implications for ionospheric noise reduction systems. However, the large scale electric currents can also interact with smaller scale conductivity structures both in the ocean and in the seafloor to produce both electric and magnetic anomalies whose spatial scale can be comparable to targets of naval interest.

Assessing the impact of the large scale structure on naval applications requires some understanding both of the large scale conductivity structure which is responsible for current concentration (the so-called coast effect) and the magnitude and scale of local conductivity inhomogeneities which are in turn excited by the large scale electric currents. These include local geologic bodies and conductivity contrasts within the seawater. Since these smaller scale structures are primarily the province of other discussion groups, we will concentrate on the problem of defining the large scale conductivity structure and hence the exciting field. However, the experiments needed to study these effects will overlap strongly with those needed to study almost all other sources of noise.

The actual edge of the ocean represents the most obvious (and easily modeled) mechanism for local electric current concentration. However, images of the electric currents in the ocean flow at depth in the mantle and have a very strong impact on the strength of the total anomalous EM fields that are measured. Furthermore, it is apparent from previous work that lateral variation of the deeper structure also represents a major component of the coast effect. Thus, one cannot divorce study of the large scale electrical structure from studies of the effects of conductivity anomalies within the continental shelf.

Passive margins, such as occur on the Atlantic seaboard of the US, are presumably underlain primarily by continental basement and the volcanics associated with rifting. These are commonly covered by deep sedimentary formations and may also be intruded and underplated by plutonic rocks emplaced during the rifting process. The nature of both the electrical structure within the relatively wide shelf and of the electrical transition at mantle depth is essentially unknown. No magnetotelluric or geomagnetic depth sounding data have ever been collected in this area. While a considerable quantity of multichannel seismic data exist throughout the US passive margins, it is extremely difficult to postulate a believable electrical model from seismic data alone. Model studies will have large uncertainties without the collection of EM data aimed at understanding the large scale (deep) electrical structure.

Active margins, such as occur in the Pacific Northwest, are better understood primarily because of the EMSLAB experiment. Active margins generally have a narrower continental shelf and are underlain by accreted seafloor and recently accreted wedge sediments. Active hydrologic and metamorphic processes involving widespread transport of ionic fluids are of great scientific interest and undoubtedly play a very important role in the electrical structure. The EMSLAB experiment has already gone a long way toward characterizing an electrical transect from the Juan de Fuca Ridge about 400 km offshore across the Cascade Mountains in Oregon. However, an extremely important data gap exists from the base of the continental slope to the shoreline. This gap must be filled if we are to extract even a baseline model for the large scale electrical structure of this active margin.

The appropriate way to characterize the coast effect and to study many of the coherence and correlation properties of the background EM noise is by array studies on the shelf supplemented by sensors on the nearby land and deep seafloor. We suggest undertaking two such studies, one on the Atlantic passive margin of the US and a second one on the Pacific coast. Both studies should be performed along transects with good structural control from seismic reflection and refraction, potential fields, and well logs where possible. Clearly, the EMSLAB transect off Oregon is attractive for the west coast experiment because much of the necessary information already exists. A recent National Research Council report advocates the development of a research initiative to study the deep seismic structure of the continental margins with a major purpose of testing hypotheses for their formation. Coordination of electrical studies with such ongoing programs which use state-of-the-art multichannel seismic reflection and other geophysical tools is strongly recommended. Placing EM transects along seismic transects would yield substantially better insight to the deep structure of continental margins than either approach could give by itself.

The experimental layout required is fairly straightforward. We envision an array of a fairly large number of electric field sensors along a transect perpendicular to the coast in an area where two dimensionality of the deep structure is reasonably expected to hold. The latter is necessary because our capability to model 3D structures is limited and would in any case require an unreasonable amount of data. The array spacing should be variable to test a variety of hypotheses about the possible presence of static distortions of the electric field. The instruments should operate simultaneously to allow coherence and correlation length studies to be performed and should cover the band from 10^{-6} to 1 Hz. While this lower frequency limit is below the one of immediate naval interest, data at frequencies between 10^{-6} and 10^{-3} Hz is essential for determining the deeper electrical structure. There should be concentrations of instruments in areas of likely 3D fields such as canyons and in areas of great geologic interest such as the intersection of the thrust plane with the seafloor at an active margin. This will require a careful review of existing marine geophysical data prior to deployment. Finally, it is likely that the magnetic field will be much more uniform along the transect than the electric field, and it need not be measured at every site.

Strong arguments can be made for a new generation of seafloor instrumentation for these experiments since shallow water presents different environmental and signal problems than deep water. Most of the existing instrumentation is at least a decade old in design and was intended to operate at lower frequencies on the deep seafloor. However, a credible experiment could probably be mounted using existing instrumentation.

For the shallow continental margin the principal interpretation problem is to understand what is continental material that happens to be underwater. Thus, we expect to ask some of the same questions that are applied to the onshore continental crust. For example, is there a lower crustal region of relatively high conductivity under the margins as there is on land? Furthermore, there are questions that are specific to continental margins. Can we measure the conductivity and thickness of the relatively porous layer of recent sediment and how well resolved are conductivities below this layer? Answering these questions requires attacking one of the major issues concerning physical explanations of conduction in the lower and middle crust. There are good reasons behind each of the two principal hypotheses, a free fluid phase at porosity levels of order 10^{-3} to 10^{-4} or the presence of a far smaller amount of graphite or amorphous carbon on a grain boundary scale. A balanced approach to understanding the electrical environment of the continental shelf includes gaining some understanding of the physical and geological causes of the conductivity. Hence, there should be a complementary program of laboratory studies of conductivity of crustal rocks. It is only by gaining a physical understanding of observed anomalies that information at one locale can be extrapolated to another.

Appendix G
Small Scale Electrical Structure Working Group Report

A. Schultz (chair), C.S. Cox, R.N. Edwards, J.A. Hildebrand,
E. Mozley, T. Shankland

The ability to distinguish the electromagnetic signature of submarine targets from the background EM spectrum is complicated by a number of factors related to small scale sub-seafloor and water column structure, composition, and dynamic state. These may affect our ability to remove ionospheric or oceanic noise from EM measurements. Thus, the overall question considered by this working group is "what is the electrical granularity of the ocean/continental margin and why might it be important to the Navy?".

Motion in the deep sea makes it a low impedance generator of electromagnetic energy, and its high conductivity makes it an efficient collector of externally generated disturbances. This energy is available to force electric current into the more resistive continental rocks. The continental shelves provide an extended and thin conducting seawater wedge that provides the electrical connection between the deep sea and the continent. One expects that a high density of electric current flow will go through the seafloor on the shelves. The major questions are where and how uniform will the electric current flow be? Certainly there will be tendency for concentration of the currents into those areas which have an extended contact with the continental rocks such as inlets, salt marshes, rivers, and other obvious geographic features. The degree to which these tendencies are effective will depend on the details of the conductivity structure within the rocks forming the adjacent current paths. These are problems of the immediate shoreline, but quite possibly similar small scale conductivity structures in the rocks provide electrical channels under the open waters of the continental shelves. The scientific question to be addressed here is the location and mechanisms of coupling between the oceans and the continents, matters of importance for interpretation of electromagnetic measurements both on the shelves and in the deep sea, as well as of intrinsic interest in connection with understanding the geological structure and history of the continental borders.

Some information on the granularity of electrical conductivity on shelves is available in the voluminous borehole data base obtained in the process of exploration for oil. These data are largely limited to sedimentary structures in deep sedimentary basins, and are at depths shallow compared with the thickness of the crust. The electrical connections of sedimentary basins to lower crustal rocks are not well understood even on land, and still less so on shelves. The possibility of anomalies of conductivity in the crust underlying the continental shelves, hidden from conventional geological exploration by the veneer of sediments, has to be considered as likely when one considers the very large range of conductivities found in common rocks and the modifications to that conductivity provided by fluid filled cracks and pores, neither of which is readily found even by seismological methods. There is little knowledge available at present to describe this granularity.

These remarks emphasize the importance of performing experiments that trace out the electrical connection between the deep sea and the continents by way of the continental shelves. In so doing it will be important to make exploratory studies to describe the shape and location of anomalies on the continental shelf and slope before a major experiment can be profitably designed. For example, a concentrated effort involving many EM stations on a line normal to the shore could show badly distorted electric flow if current channeling in the crust localizes the flow.

Anomaly mapping can be carried out by controlled source methods which focus on the shallow structures and by examining the patterns of the electric field existing on the shelf in response to the large scale, naturally induced fields offshore. The latter will provide a view of the overall inhomogeneity whether produced by deep or shallow structures. The combination of the two methods will give insight into the interplay of shallow and deep structures in establishing small scale inhomogeneities. Thus, the major task to address small scale problems must be collecting enough measurements of the local conductivity structure to begin characterizing continental shelf variability. Only when this information is in hand can questions about its importance to either geophysical or naval problems be addressed.

There are in addition some secondary sources of small scale EM noise that might deserve consideration. As is well-known to be the case for the magnetic field, there is also a DC (or quasi-DC) component to the seafloor electric field. Self potentials (SP) resulting from the presence of electrochemical, thermoelectric, and electrokinetic processes are probably the chief cause of DC electric fields, and very little work has been done to date on either measuring or modeling their effects. These fields are expected to be of small scale (a few to a few hundred meters). Furthermore, the electrical conductivity of the near surface sediments may well be time dependent on long (months to years) time scales. The influence of varying sedimentation rates on the interaction of large scale induction fields as well as SP fields is currently unknown. It will be necessary to evaluate the repeatability of conductivity measurements over time in order to gauge our ability to distinguish transient sources from ambient background.

Another closely related factor is understanding the role of fluid flow in the seafloor on the spatial (and possibly temporal) variations in conductivity. The issue of subsurface fluid flow needs careful consideration. A large data base of well log information exists in oil companies for the continental margins. Indications are that the conductivity, and by inference the porosity, of the sediments decreases rapidly within the first few hundred meters of the surface, suggesting a rapid pinching off and filling in of pores, cracks, and interstitial spaces at relatively shallow depths. Despite this, considerable evidence exists for outward flow of fluids from sediments at convergent margins. The question is then raised of how the fluids flow through or are trapped in the subducting sediments, influencing the conductivity structure. This issue can only be resolved by a program of measurements.

In designing an experimental program, three geographic areas merit special attention. These are a part of a steeply sloping convergent margin, a shallow sloping passive margin, and a representative Arctic terrain. Piggy back operations with passive electric field measurement programs also planned for such locales are appropriate and economical. Considerable information can be obtained by utilizing the passive electric field sensors in a high density sampling and stacking mode together with a horizontal electric dipole towed along the seafloor by a surface ship. The source signal will be transmitted to the receivers via the seafloor, yielding information on its electrical conductivity. The variability as the source dipole is moved gives information on lateral changes in bottom conductivity. The exact locations of these experiments is not critical and probably should be guided by the needs of large scale structure or oceanic source experiments. However, the EMSLAB area in the Pacific Northwest certainly is suggested as a logical convergent margin site.

In addition, a finer scale mapping program is needed at one representative site. This could include potential fields (deeptow magnetometer, self potential electric field, temperature), active source dipole-dipole conductivity work, use of the electric signal propagating in the ocean to map variations in near-bottom seawater conductivity, sub-bottom profiling, shallow water bathymetric techniques to provide high resolution control on seafloor topography, side scan acoustic reflectivity sonar to map areas of sediment cover and exposed rock, possible control of seismic velocity structure using OBS's, possible tie-ins with existing drill holes as well as shallow vibracores and gravity cores, tie-ins with seismic lithology, and possible tie-ins with meteorological and physical oceanographic observations in the same area. The thrust of the mapping program is to understand the impact of the underlying geological framework on the ambient EM fields. This needs to be carried out in one or more areas in order to fully sample a range of environmental parameters.

Coincident with these field programs, it will be necessary to push towards a number of developments in modeling the interaction of finite wavelength EM fields, including oceanically-induced types, and 3D conductivity structures. Other developments must proceed in the interpretation of active source EM measurements, including appropriate signal processing and inverse theory. It may also be necessary to initiate work on modeling the generation of quasistatic electric fields by gradients in chemistry, temperature, and fluid pressure within the seafloor. It is important to assess their possible role in the overall picture. A major goal has to be better defining the natural length scales that are operative if this information is to be useful to the Navy.

Further work on laboratory measurements of candidate rock electrical conductivity is also warranted, as was noted by the large scale working group. It should be remembered that explaining electrical profiles in terms of geology and physical properties works both ways. When valid explanations of conductivity exist for a carefully studied region, then there will be a logical basis for estimating electrical properties in other regions where the geology is understood, but no electrical measurements are available.